the GENERAL RADIO Experimenter

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TO

GENERAL RADIO
EXPERIMENTER

VOLUMES XVI AND XVII

June, 1941 to May, 1943

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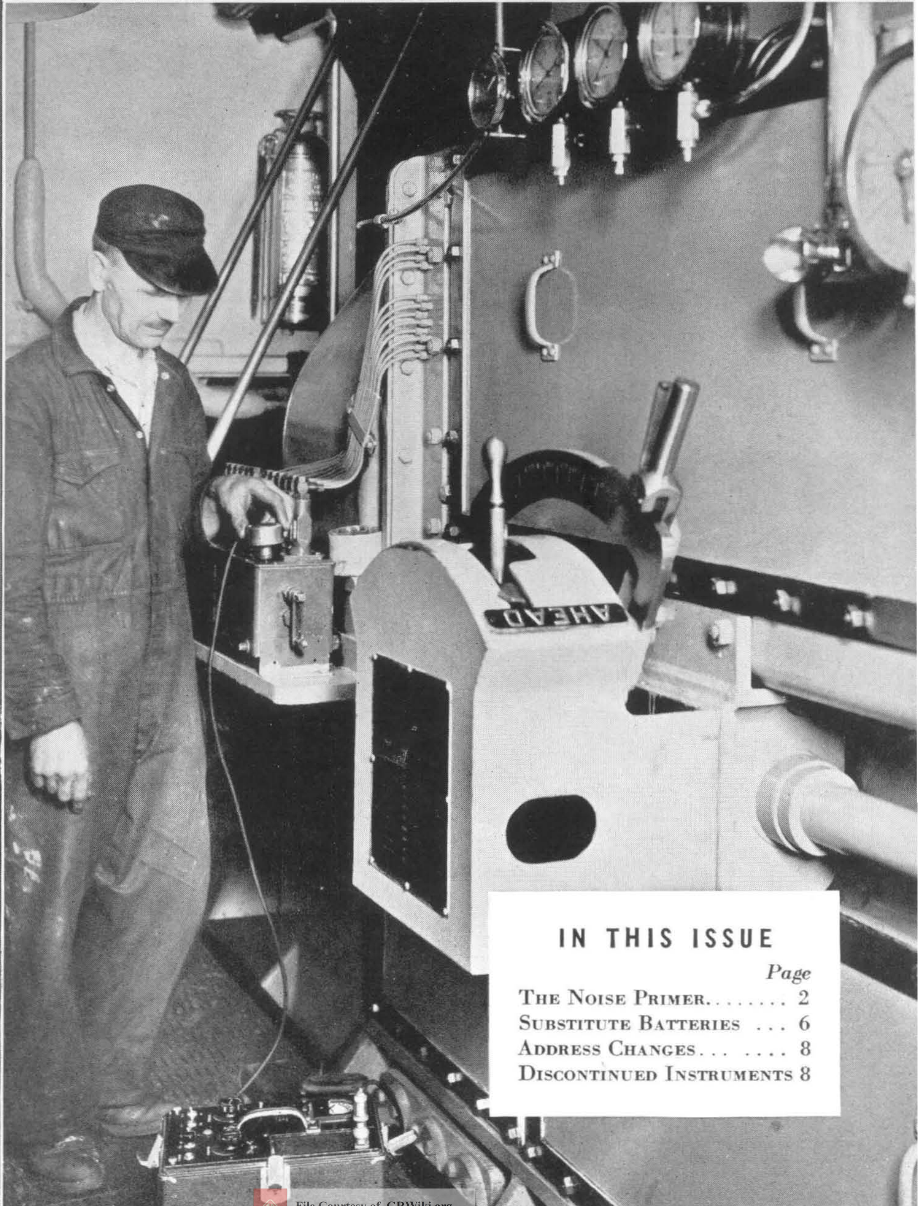
ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS



IN THIS ISSUE

COVER PHOTOGRAPH
Measuring Vibration on a Diesel Trawler with the Sound-Level Meter and Vibration Pickup.

THE NOISE PRIMER

● **IN THESE DAYS OF SECRET DEVELOPMENTS** there is much technical information which cannot be published and many new developments which cannot be advertised for general sale. This is a good time, therefore, to provide additional information covering instruments and techniques which were developed and known before the war.

With this issue, we begin a short series of articles dealing with the measurement and analysis of acoustic noise and mechanical vibration. To many it will be an old story, but for a number of industrial users of General Radio sound and vibration measuring equipment it may provide the answers to many of their questions.

Bulletins 20 and 30 ("The Technique of Noise Measurement" and "The Technique of Noise Analysis," respectively) have been in print for several years, and the General Radio Company has also published several other bulletins and *Experimenter* articles covering the general subject. However, most manufacturers of sound and vibration measuring equipment (and General Radio is no exception) are inclined to overlook as obvious many small details of theory and procedure which baffle the uninitiated. These articles are, therefore, both an apology for this "everybody-ought-to-know-that" attitude and a real attempt to help the many who in the past have had no more reason to know about sound measurements than the communications engineer has had to know about blowers or turbines.

Most manufacturers are convinced that customers never bother to read instruction books. Not to defeat their purpose, then, these articles must of necessity be brief, and we only hope that we haven't left out anything of real importance to you.

PART I—TO BUY OR NOT TO BUY

(If you don't have a high priority rating, reading this part may be a waste of time.)

Treatises on sound and vibration measurements generally start with a long-winded discussion as to their importance, but this is now so well known that we shall assume that you wouldn't be reading this at all if you weren't convinced. We shall therefore dispense with all unnecessary formalities.

The aura or mystery which surrounded early sound measurements has gradually been dissipated. The long-haired scientist who waved the microphone, gazed at the meter, went into a trance and came out with a lot of mysterious numbers has gone, along with the notion that ability to tolerate noise is a mark of giant brain power. There is still plenty of work for the consultants—on problems of a temporary or unusually difficult character, but all measurements connected with the normal development or manufacture of a product are now generally carried out by the manufacturer's own engineering or production staff.

If, in the design, manufacture, or sale of your products you have regularly to measure or to analyze noise or vibration, you or others in your organization should be able to make the measurements quickly and accurately. For shorter jobs, you must balance the cost of the equipment (which is now surprisingly low) and the time against the possible consultant's fee. One important thing to remember is that, once the equipment is purchased, you have it, and it will also be very useful, perhaps invaluable, on future problems. The demand for quietness and freedom from vibration is becoming more insistent. Do not, therefore, assume that your present problems are only temporary, or that you will never have any more like them. Do not deny your organization the advantages now of something you will probably need even more as time goes on. Noise and vibration are not merely annoyances which may affect the sale of a product or lower the efficiency of a worker. They are often evidences of defects in design and manufacture which seriously affect the life of the equipment and in many cases the safety of the user.

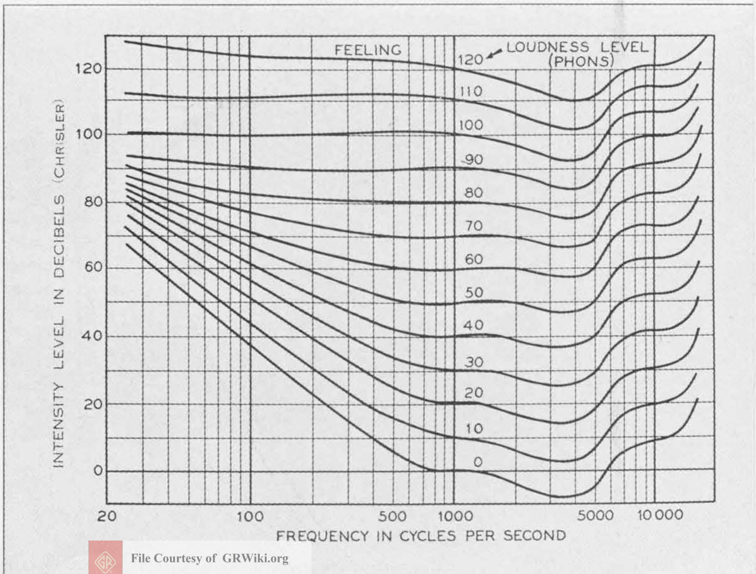
PART II—THE SOUND-LEVEL METER

Similarity to Ear

The sound-level meter or, as it is often called, the noise meter, is essentially a device for measuring the amplitude of rapid alternations in the air pressure. It does not measure the frequency, or pitch, at which such alternations take place. When these alternations occur within a certain range of frequencies they affect the ear and are known as "sound" or "noise." The sound-level meter is intended, therefore, to provide a simple means of obtaining objective measurements which can be correlated with the response of the average ear.

Don't think that the sound-level meter is perfect in this respect. Not enough is now known about the ear to enable us to duplicate its response perfectly and, even if it were, the necessary equipment would be complicated, bulky, and expensive. Furthermore, for many engineering problems the conventionalized response of the sound-level meter is more useful than an exact ear response would be, since the ear response, by its complicated nature, is not subject to simple mathematical or physical analysis. As long as we realize

FIGURE 1. Equal-loudness contours for the average ear.[1]



its limitations the sound-level meter is a most useful device, and certainly the best thing for its purpose which can be devised at the present time.

As an example of the many complicated characteristics of the ear, Figure 1 shows the familiar Fletcher-Munson curves, which are constant-loudness contours of the average ear in terms of frequency and loudness level. These indicate that the frequency-response characteristics of the ear are not constant. but vary with the loudness of the sound. For instance, at low sound levels the ear is relatively insensitive to low frequencies, but at high sound levels it hears them almost as well as the higher frequencies.

The best known makes of sound-level meters are more or less alike. are all intended to follow the sta s as set forth by the American Standards Association,[2] and with the passing of time all leading manufacturers have adopted similar mechanical and operating features. For most purposes they may be considered interchangeable, but in some few cases their readings will not be identical, although the meters may all meet the standards.

Microphone Limitations

A glance at Figure 2 will show one reason why this is so. The tolerances, which may seem excessively wide to those previously unacquainted with acoustical measurements, are made necessary by the limitations in available microphones. Most microphones were originally designed for use in the reproduction of music and speech and are not for purposes of quantitative measurement. There are many factors entering into the reproduction of speech and music (such as the ear, room acoustics, and the properties of the instruments and voice) which make it useless to maintain an absolutely flat or smooth frequency-amplitude characteristic in the microphone, particularly if it must be obtained at the expense of sensitivity or other desirable properties. Hence the

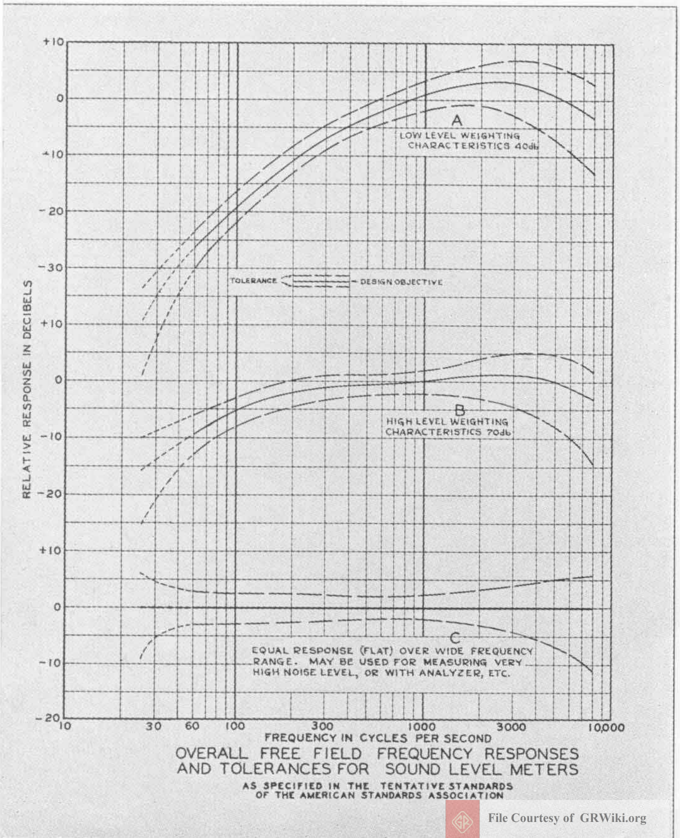


FIGURE 2. Design objective frequency-response curves between 60 and 8000 cycles for sound-level meters as specified by the American Standards Association (Bulletin Z24.3—1936). These standards do not specify the response below 60 cycles. The extended curves represent present practice as followed by the General Radio Company in the TYPE 759-B Sound-Level Meter.

characteristics of standard microphone types vary considerably from a straight, flat line, particularly in the extreme upper and lower parts of the audible range. While, in many cases, the microphones used for sound measurement are improved in this respect over those commonly used for broadcasting and recording, the perfect microphone is yet to be developed, and present types all represent a compromise in order to get the best possible combination of good frequency response, stability, ruggedness, and sensitivity. The tolerance curves of Figure 2 represent the maximum deviations from a given design objective to be expected with the best of present microphone types. So far as the electrical circuits in the sound-level meter are concerned, it is possible to make these follow any particular characteristic with a high degree of accuracy.

The microphone, then, is the weakest link in the sound-level meter, but the situation is actually much better than the tolerance curves would seem to indicate. Figure 3 shows, in column 2, the relative sound pressure in average noise for the various frequency bands tabulated in column 1. It will be noted that the high frequencies become progressively less important, so that for most purposes components above 3000 cycles may be omitted altogether without serious error. Since a sound-level meter, in order to meet the standards, must have a certain amount of response up as far as 8000 cycles, it follows that, for sounds of general character, it will read quite accurately, providing it has a good low-frequency response, which is much more important.

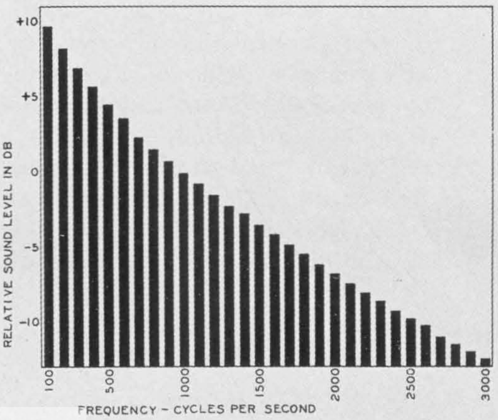


FIGURE 3. Chart of the relative contribution to total noise level made by 100-cycle bands over the frequency spectrum, as obtained from analyses of noises of a general character. (From A.S.A. Bulletin Z24.3 — 1936.)

Of course, there will always be some sounds with strong components above 3000 cycles or at very low frequencies, and it is on this type of sound that the greatest error will generally occur. The most serious discrepancies among different meter types generally happen when a strong component is at a frequency where one microphone has a valley in its response curve while the other has a peak. As an extreme, at 8000 cycles a possible difference of 15 decibels could result from this cause alone with meters meeting the standards in every way. In actual practice, however, differences even a fraction as large as this are uncommon, and occur only in exceptional cases. Also, errors from this cause may be almost entirely eliminated through the use of an analyzer and a calibrated microphone, as will be described later.

A.S.A. Frequency Response Curves

Now that we know the worst that can occur, we can forget it for a while and go on to more practical and important aspects of the sound-level meter. It should be noted that the curves in Figure 2 bear a close resemblance to those in Figure 1 and were actually derived therefrom. Since the A.S.A. committee realized that it was neither desirable nor practical to duplicate the ear response exactly, the curves for two representative levels (40 and 70 db) were taken from Figure 1, modified for random free-field response and smoothed.[3] The flat response (C) was added for use where measurements of actual physical sound pressures were desired and at very high sound levels, where the ear response is fairly constant.

In addition, the A.S.A. standards (Z24.3) define various terms and units, specify other tolerances, and how the microphone is to be calibrated. Many of these points will be discussed in later articles. The standards are the result of some years' experience in the design, manufacture, and use of sound-level meters, and are now in the process of revision in some minor details. These revisions are not of the nature that will make present types of meters obsolete, however, but rather bring the standards more in line with what can be accomplished in the present state of the art by the leading manufacturers. Complete information regarding the modified standards will be supplied as soon as it is available. — H. H. SCOTT

(To be continued)

REFERENCES

[1] These curves are now incorporated in the American Standard for Noise Measurement, Bulletin Z24.2 — 1942, published by the American Standards Association, 29 West 39th Street, New York, N. Y. (price 25 cents). They were originally published in a paper by Harvey Fletcher and W. A. Munson of the Bell Telephone Laboratories entitled "Loudness, Its Definition, Measurement, and Calculation" and published in the Journal of the Acoustical Society of America, Vol. VI, No. 2, pp. 82-108, Oct., 1933. Curves of a similar nature, but based on earlier data, were published by B. A. Kingsbury, "A Direct Comparison of the Loudness of Pure Tones," Physical Review, Vol. XXIX, p. 588, 1927.

The Fletcher-Munson curves were based on a group of individuals whom later experience has shown to have somewhat better than average hearing. More recent tests, as reported by Dr. Fletcher, have indicated that for the average person the threshold of hearing is somewhere between 10 and 20 phons.

[2] American Tentative Standards for Sound-Level Meters for the Measurement of Noise and Other Sounds (A.S.A. Bulletin Z24.3 — 1936).

[3] The curves in Figure 1 represent measurements made on one ear at a time (monaural) with a plane wave — that is, a wave striking the ear at a single given angle. The irregularities above 1000 cycles are due in large part to diffraction effects caused by the shape of the head or the outer ear. The curves in Figure 2 have been modified to duplicate as nearly as practical the response of the ear to sounds arriving equally from all directions. The smoothing allows the curves to be more easily duplicated by simple electrical circuits and is justified by the fact that binaural hearing eliminates many of the irregularities present in the curves of Figure 1.

SUBSTITUTE BATTERIES FOR BATTERY-OPERATED EQUIPMENT

● **THE PRESENT DIFFICULTY** in obtaining new batteries above the requirements for current instrument production has necessitated a curtailment of our regular policy of maintaining a stock of replacements, and users should try to buy them locally.

The standard batteries recommended for General Radio instruments may not be available in some localities. Substitutions of different types or combinations of different types are quite permissible if certain precautions are observed. The substitutes must have the same voltage as the standard types and be capable of delivering as much current. When these are mounted externally the leads used must be at least as large as the connecting leads in the instruments. In some cases, shielding is necessary. The following table should be helpful if the standard batteries are not readily available.

SUBSTITUTE BATTERIES FOR BATTERY-OPERATED EQUIPMENT

Type		*Batteries*	*Possible Substitutes*
419-A	Wavemeter	1 No. 6 Dry Cell	Shortage unlikely.
544-B	Megohm Bridge	2 No. 6 Dry Cells 3 Burgess 5308	Shortage unlikely. 1 90-volt block and 1 45-volt block, mounted externally.
613-B	Beat-Frequency Oscillator	2 No. 6 Dry Cells 3 Burgess 5308	Shortage unlikely. Any 135-volt combination, mounted externally, if necessary.
625-A	Bridge	2 Burgess 2370	Any 4.5-volt combination; dry cells are satisfactory.
650-A	Impedance Bridge	4 No. 6 Dry Cells	Shortage unlikely.
723-A	Vacuum-Tube Fork	1 Burgess 4FA	1 No. 6 dry cell, mounted externally.
		2 Burgess Z30N	Any combination supplying 90 volts; leads must be short.
724-A	Wavemeter	1 Burgess 4FA	Not recommended; any change in dimensions or location will affect the calibration.
727-A	Vacuum-Tube Voltmeter	3 Burgess 2F (1.5-volt) 2 Burgess W20P1 (30 v) 1 Burgess W58P (7.5 v)	External batteries giving the same voltages can be used, but leads must be short.
729-A	Megohmmeter	1 Burgess 2F2H (3 v) 2 Burgess W30BP (22½, 45 v)	See TYPE 727-A.
759-A	Sound-Level Meter	2 Burgess 4FA (1.5 v) 2 Burgess Z30N (45 v) 1 Burgess F2BP (3 v)	If external batteries are used, battery box must be shielded and leads must be short. Battery box shield must be connected to instrument shield.
759-B	Sound-Level Meter	1 Burgess 6TA60	If external batteries are used, see TYPE 759-A, above. One user has reported that two small 45-volt batteries and one 1.5-volt unit, which will fit in the battery compartment, can be obtained at Sears-Roebuck retail stores.
760-A	Sound Analyzer	3 Burgess Z30N 4 Burgess F2BP	See TYPE 759-A.
761-A	Vibration Meter	1 Burgess 6TA60	See TYPE 759-B.
814-AM	Amplifier	2 No. 6 Dry Cells 3 Burgess 5308 1 Eveready 950	Shortage unlikely. Any 135-volt combination. Any 115-volt flashlight cell.
814-AR	Amplifier	2 Burgess 4FA 3 Burgess Z30N 1 Burgess 2370	Same as TYPE 814-A, above.

ADDRESS CHANGES AND ADDITIONS TO THE "EXPERIMENTER" MAILING LIST

● **WE HAVE RECEIVED** a number of complaints lately from *Experimenter* readers who have not received the last few issues of the *Experimenter*. We regret the delay in making address changes and in adding new names to our mailing list, but the cause is entirely beyond our control. Owing to the press of other war work, the company that cuts our mailing list stencils is unable to give us deliveries better than 60 days.

In some cases, *Experimenters* are delayed where no address change is involved. This is usually caused by a damaged stencil, which necessitates the cutting of a new one.

We can only ask your indulgence, and we will do our best to make the delay as short as possible. When your new stencil is received, back issues that you have missed will be mailed to you automatically.

A number of readers whose addresses are continually changing because of war conditions are now having the *Experimenter* sent to their homes to be forwarded. This is an excellent way to be sure of receiving all issues.

DISCONTINUED INSTRUMENTS

In order to conserve materials and facilities necessary for the production of more urgently needed equipment, the following items have been discontinued:

Type 449-A Adjustable Attenuator

Type 713-BR Beat-Frequency Oscillator (Relay Rack Model)

The Type 713-BM (Cabinet Model) is still in regular production.

THE General Radio EXPERIMENTER is mailed without charge each month to engineers, scientists, technicians, and others interested in communication-frequency measurement and control problems. When sending requests for subscriptions and address-change notices, please supply the following information: name, company name, company address, type of business company is engaged in, and title or position of individual.

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VOLUME XVII No. 9 FEBRUARY, 1943

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also

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THE NOISE PRIMER

PART III

THE DECIBEL—WHAT IS IT?

● IN SOUND MEASUREMENTS the results are expressed in decibels. The higher the number of decibels, the louder the sound. Zero decibels represent roughly the weakest sound which can be heard by a person with very good hearing. In practical noise measurements anything below 24 decibels can generally be considered so nearly inaudible as to be of no importance. In fact, except in unusually quiet locations, noises below 40 decibels may generally be disregarded.

From the strictly technical standpoint, a given number of decibels represents a ratio, since the decibel is a logarithmic unit. In terms of sound pressure the formula is

$$\text{db} = 20 \log_{10} \frac{E_2}{E_1} \qquad (1)$$

where E_1 and E_2 represent the two sound pressures being compared.[4] This applies only under conditions where the power is strictly proportional to the square of the pressure, which is generally

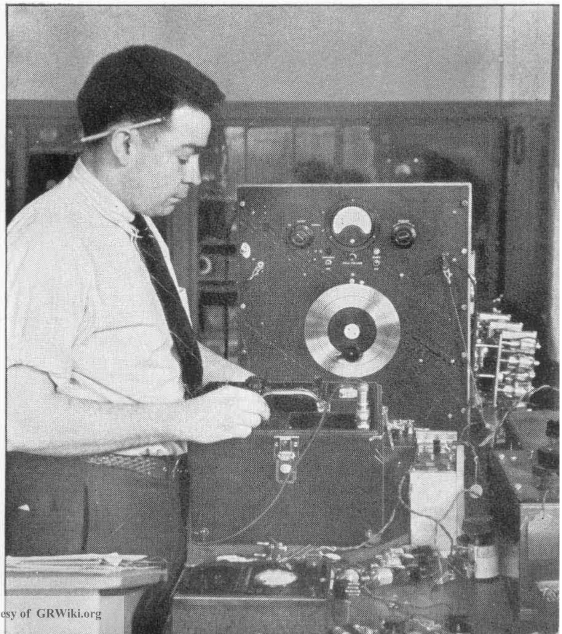

FIGURE 4. Calibrating a TYPE 759-B Sound-Level Meter in the General Radio standardizing laboratory.

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[4] This is the same formula that is used in electrical communications to compare two voltages operating at the same impedance levels.

true for sound measurements in air.

In sound measurements decibels represent not merely ratios, but absolute levels, since a standard reference level has been agreed upon. This level is 0.002 dynes per square centimeter at 1000 cycles.[5] This reference level is approximately 16 db below the average threshold of hearing.[6]

Do Not Add Decibels

Since the decibel is essentially a logarithm, addition of decibels produces multiplication of sound pressures. For instance, increasing any sound level by 6 decibels is equivalent to doubling the sound pressure. Do not try, therefore, to add two sound levels together by ordinary addition. Sounds of a general and complex nature add approximately as the relative sound power involved. That is, two sounds of equal power, when added together, produce twice the power, which is $\sqrt{2}$ times (not twice) the sound pressure.

The Equation (1) for decibels expressed in terms of sound pressure represents a special case which is valid only because, under conditions generally encountered, the air has a constant impedance. The more fundamental equation is expressed directly in terms of power and is

$$\text{db} = 10 \log_{10} \frac{P_2}{P_1} \qquad (2)$$

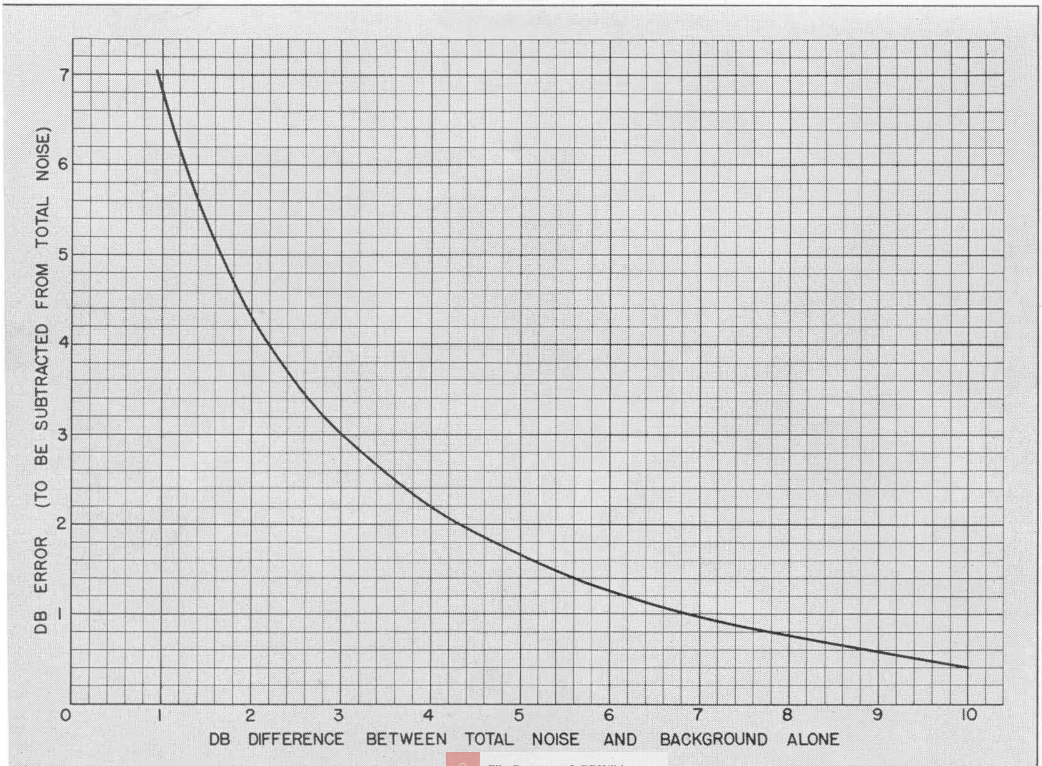
where P_1 and P_2 are the sound powers

---

[5] Sound-level meter microphones respond to sound pressure. 0.0002 dynes per square centimeter is the practical equivalent of 10^{-16} watts per square centimeter, as specified in the American Standards Association Bulletin Z24.3—1936.

[6] See Steinberg, Montgomery, and Gardiner, "Results of the World's Fair Hearing Tests," Journal of the Acoustical Society of America, Vol. XII, No. 2, pages 291–301, October, 1940.

FIGURE 5. Error introduced in sound measurements by background noise (from L. E. Packard, "Background Noise Corrections in the Measurement of Machine Noise," General Radio *Experimenter*, Vol. XII, pp. 6, 7, Dec., 1937).



involved.[7] The standard zero reference level in terms of power is approximately 10^{-16} watts per square centimeter at 1000 cycles.

A slide rule, logarithm table, or, more conveniently, a decibel table (obtainable on request to the General Radio Company) is accordingly necessary for adding together sound levels expressed in decibels.

As an example, assume a sound of 50 decibels is to be added to one of 53 decibels. Looking in the decibel table, we find that the first represents a relative power ratio of 10^5, while the second represents a relative power ratio of 2×10^5. Adding these together, we get a total of 3×10^5, which is equivalent to 54.8 decibels.

A simple relation to remember is that doubling the sound power is about equal to an increase of 3 decibels, so that when equal sound levels are added together, regardless of their actual value, the resulting level is 3 decibels higher than that of the originals. Thus, 40 db + 40 db = 43 db, etc. If you add to a first sound a second which is 10 db lower in level (1/10 power) the resulting level is 0.4 db higher than the first sound alone, which is a negligible increase for most purposes.[8]

Background Noise

One of the most frequent applications involving the addition or subtraction of sound levels is the correction of readings for background noise. Ordinarily, of course, sound measurements should be made under conditions where the background noise level is negligible — that is, at least 10 db below the level being measured. However, this is not always possible, and the curve shown in Figure 5 is convenient in those cases. The horizontal scale of this chart represents the difference in sound-meter reading with and without the machine under test in operation. The vertical scale represents the number of db to be subtracted from the total reading (machine plus background noise) to obtain the noise level generated by the machine alone.

Loudness

It is generally assumed that the response of the ear to variations in sound intensity is logarithmic, but this is not strictly true. Figure 6 represents the actual relationship between the loudness as estimated by a large number of observers and loudness level. This curve shows loudness in L. U. (Loudness Units) plotted versus loudness level in phons.[9] Loudness level in phons is equivalent for most practical purposes to

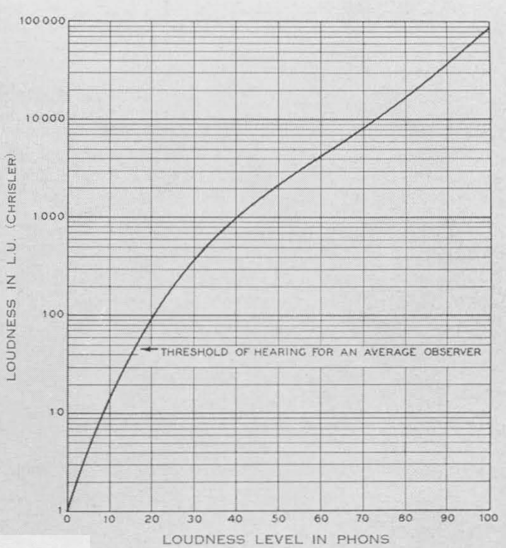


FIGURE 6. Relation between loudness level, from "American Standard for Noise Measurement," American Standards Association Bulletin Z24.2—1942.

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[7] This is the exact equivalent of the electrical case, and the formula is the same as that which applies in general communications problems, where zero level is usually 1 milliwatt in a 600-ohm line.

[8] The exception to this would be when the two sounds were of markedly different character. This will be discussed in a later article.

sound level as measured by a sound-level meter, assuming that the meter has exactly the correct frequency response for the particular level being measured.

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[9] A complete table of the function plotted in Figure 6 is given in the American Standards for Noise Measurement, A.S.A. Bulletin Z24.2—1942. This information is based upon the paper by Fletcher and Munson in the October, 1933, issue of the Journal of the Acoustical Society, referred to last month in Note 1.

In the strictest interpretation, loudness level in phons is measured by adjusting a 1000-cycle tone to exactly the same loudness as heard by the ear as the noise being measured, and then measuring the intensity of the 1000-cycle tone as with a sound-level meter. Loudness level and sound level correspond exactly, therefore, only for 1000-cycle tones.

As a practical matter, a sound-level meter, when the network corresponding most closely to the level being measured is used, provides readings closely approximating loudness level in phons. Phons and loudness units are seldom used in machinery noise problems, but do have some application in physiological and psychological work.

PART IV

HOW TO USE A SOUND-LEVEL METER

Operating Instructions

Manufacturers have tried to make sound-level meters as simple to operate as possible. The instruction sheets covering the actual mechanics of operating General Radio Company's Type 759-A and Type 759-B instruments are mounted in the covers. For those who may be unacquainted with the instruments, however, the following may be of interest.

A standard sound-level meter has, aside from various minor controls, three main controls and indicators which are used in taking the readings. The first of these is a knob generally marked "Weighting" and providing choice of any of three frequency characteristics shown in Figure 2 of last month's article. The second is a knob generally marked "Decibels," which shifts the sensitivity of the instrument in steps of 10 db. The third is an indicating meter calibrated over a range of approximately 16 db, which in effect interpolates between the readings of the decibels control. In operation the reading of the meter is added to that of the decibels control.

Other controls are generally provided for checking the calibration, changing the meter speed, etc.

FIGURE 7. Panel View of the General Radio Type 759-B Sound-Level Meter.

Test Code

The American Institute of Electrical Engineers has formulated a test code covering certain standard methods of procedure particularly well adapted to the measurement of noises made by electrical machinery. The code is by no means complete and consequently does not apply in all cases, but it does form a basis for more specialized codes applying to individual applications.[10] In particular, it specifies standard test distances which can generally be followed in almost all cases. The standard test distances are 6 inches, 1 foot, and 3 feet. The distance should be measured between the nearest major surface of the machine under test and the microphone. When the microphone is mounted close to or on the sound-level meter case, that end of the case should face the sound source.

Microphone Placement

Remember that the sound-level meter measures sound pressure *at* the microphone, and that the sound pressure varies throughout a normal room and around a machine or other sound source. Microphone placement is probably the most important operation in the noise measurement procedure and about the only "trick" that has to be mastered by the beginner.

To measure with great accuracy the total noise output from a machine, it would be necessary to take an infinite number of measurements all around the machine and integrate the results. In actual practice measurements are made at equal intervals around a machine and at a fixed distance from it, the actual number of such measurements depending upon the complexity of the sound pattern and the importance of the results. Where extreme accuracy is not required, and particularly when the readings to be averaged are within a range of 10 decibels or so, a simple arithmetic average of the decibel readings is generally sufficient.

A more exact method involves converting the decibel readings to their corresponding relative power values, averaging these, and converting back to decibels. The procedure is similar to and involves the same equation as that previously described for the addition of sound levels, except that in this case the sum of the corresponding powers is divided by the number of readings to obtain an average, as shown in Table I, below.

This is the fairest way of comparing machines of different types or characteristics, but a simpler procedure can generally be used when comparing similar machines, as in production testing.

TABLE I

Microphone Position	*Decibels Sound Level*	*Relative Sound Power (Antilog 1/10 Sound Level)*
I	50	100,000
II	55	316,200
III	70	1,000,000
IV	55	316,200
		4)1,732,400 total
		433,100 average

$10 \log_{10} 433{,}100 = 56.4$ decibels.

---

[10] A I.E.E. Test Code for Apparatus Noise Measurement, A.I.E.E. Bulletin No. 520, March, 1939, published by the American Institute of Electrical Engineers, 33 West 39th Street, New York, N. Y., price 30 cents. The test code is now being revised by the American Standards Association in collaboration with the A.I.E.E. Information on the revised code will be supplied as soon as it is available.

A test position can be selected which gives a single reading that *varies* closely with the average noise as determined by the above method. This single test position is not necessarily one giving the *same* reading as the average. Usually it will be the position providing the *highest* reading.

This procedure may be modified in individual cases. For machines having a very pronounced noise pattern, two or more test positions providing fairly high readings might be used. On such machines, it is sometimes desirable, in order to get a better check on the total noise, to measure the level at these several maxima in the noise pattern and average the results, either arithmetically or according to relative power levels. This, of course, yields an average higher than the general average, and usually a more sensitive one. It provides a fair comparison only between similar machines. In comparing dissimilar machines, only a general average, taken with as many microphone positions as necessary, will be fair.

Choice of Weighting Curve

Aside from microphone placement, selection of the correct weighting curve is the next important factor in making noise measurements. Changing the weighting curve can produce variations in the results ranging from negligible differences in the medium and upper frequency range to variations of 20 or 30 decibels at low frequencies.

When all that is desired is knowledge of the sound level at the microphone, the problem is relatively simple. The following table shows the sound-level ranges and the weighting curve recommended:

Sound-Level Range	*Weighting Curve*
24- 55 db	A (40 db)
55- 85 db	B (70 db)
85-140 db	C (Equal response over entire range)

Strict use of this table will sometimes be impossible. For instance, a sound may read 54 decibels on the A characteristic and 56 decibels on the B, due to the greater weight given to low frequencies on the B curve. Similarly, although not so likely, a sound with a large amount of energy in the region of 2000 cycles might possibly read 56 db on the A curve and 54 db on the B. There is still, therefore, some judgment required in choosing the best curve to use under these conditions, but the following procedure is generally satisfactory. If the measurement is one of a series, most of which fall well within the range of a particular curve, this setting should be used for all measurements. If no such clear-cut distinction exists, it is desirable to record measurements made with both curves, noting, of course, the curve designation as well as the level. Where actual loudness is important, rather than mere changes in loudness or physical values, it is sometimes desirable to make measurements on both curves and average the results.

Always record the weighting curve designation as well as the decibel values.

Noise at Distance

It is not always the sound level at the microphone which is important, but rather the annoyance which the noise will produce at some distance. Under these conditions the choice of the weighting curve should be based upon the level at the point where the annoyance exists, although measurements may actually be made close to the machine as a matter of convenience.

For instance, assume the problem is to quiet an airplane motor test chamber so that, with an engine running under test at full speed, neighbors some distance away will not be disturbed by the noise. Assume that at the neighbors' homes the sound has a level below 55 decibels. Measurements made on the test chamber, therefore, even though they may be made close by as a matter of convenience and at a level considerably above 55 decibels, should be made on the A (40 db) characteristic. The measurements then will be a much better indication of the value of any quieting procedure than if they were made with the B or the C characteristic, since the meter will be operating with a frequency response more nearly duplicating that of the ears of the neighbors under the actual listening conditions.

Physical Measurements

Wherever actual physical measurements of sound pressure are desired, or where the sound meter is to be used with an analyzer, it is generally desirable to use the C characteristic, which provides substantially equal response over the audio-frequency range. Reasons for this will be discussed in a later article.

— H. H. Scott

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● **WHEN YOU COMMUNICATE** with us on business or technical matters, letters are by far the most satisfactory method. They make a permanent record and allow time to prepare a well organized and complete reply. The next best method is to telegraph. This method still gives the permanent record, but it is usually less complete than a letter can be.

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To determine the delivery status of orders already placed:

Mr. H. P. Hokanson	Extension 25

To check matters of credit:

Mr. C. E. Hills, Jr.	Extension 50

To inquire about probable delivery and prices of equipment under consideration, but not ordered:

Mr. M. T. Smith	Extension 30
Mr. I. G. Easton	Extension 94

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Mr. H. H. Dawes	Extension 24
Mr. K. Adams	Extension 79

It must be emphasized that it takes time to check up on the myriad details that may be associated with an order — with luck, it may be only a few minutes, but it often takes much longer.

USE OUR DISTRICT OFFICES

● **MANY OF OUR CUSTOMERS** know that the General Radio Company maintains branch engineering offices in New York City and Los Angeles, California. This fact may have been overlooked by others recently transferred to these areas.

These offices have been established

primarily for the convenience of our customers in the regions served. Each office is in the charge of a member of our Cambridge engineering staff, who is prepared to furnish technical data regarding the instruments which we manufacture and to recommend uses and applications. Much information which ordinarily would be transmitted to the customer in letter form is available by telephone in the New York City and Los Angeles areas.

Every effort is made to keep the District Office engineers fully informed of the current delivery situation of all of the many catalog items which we manufacture. It is often possible for these offices to suggest satisfactory alternative arrangements of test equipment on which the shortest delivery can be realized.

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The engineer in charge of our New York Office, at 90 West Street, is Mr. L. E. Packard. Mr. Packard may be reached by telephone at COurtlandt 7-0850. Mr. Frederick Ireland of our engineering staff is located at our office at 1000 North Seward Street, Los Angeles, California. He may be reached at Hollywood 6321.

SERVICE DEPARTMENT NOTES

ERRATA

● **THE FOLLOWING ERRORS** have been noted in service information published in recent issues of the *Experimenter*.

November, 1942:

In the article entitled "Orders for Replacement Parts," the plug listed as TYPE 2173, page 8, should have been 2713.

January, 1943:

In the list of substitute batteries for TYPE 814-AM Amplifier, page 7, for "any 115-volt flashlight cell," read "any 1.5-volt flashlight cell."

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VOLUME XVII No. 10 MARCH, 1943

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

GENERAL RADIO COMPANY WINS ARMY-NAVY "E"

Also

IN THIS ISSUE

● **THE ARMY-NAVY "E" AWARD** for outstanding production of war materials was presented to the General Radio Company at exercises in Cambridge on February 16, 1943. The ceremony was attended by all employees of the Company, and by representatives of the Army and Navy, of local and state governments, and of local industry.

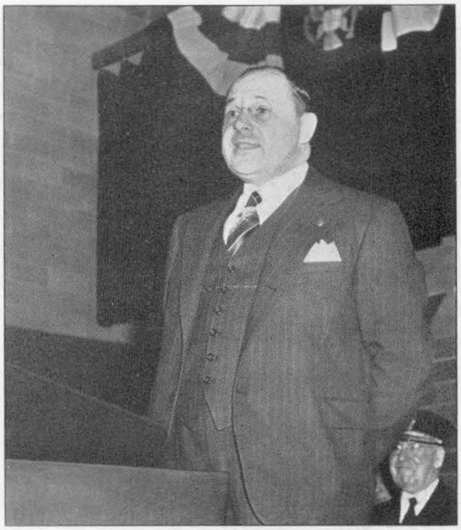
Speakers were introduced by Mayor John H. Corcoran of Cambridge. Governor Leverett Saltonstall of Massachusetts spoke briefly.

The "E" banner was presented to Melville Eastham, President of the General Radio Company, by Captain John J. Hyland, U.S.N. (Ret.), Inspector of Naval Material for the Boston district, and was accepted by Harold B. Richmond, Treasurer of the Company.

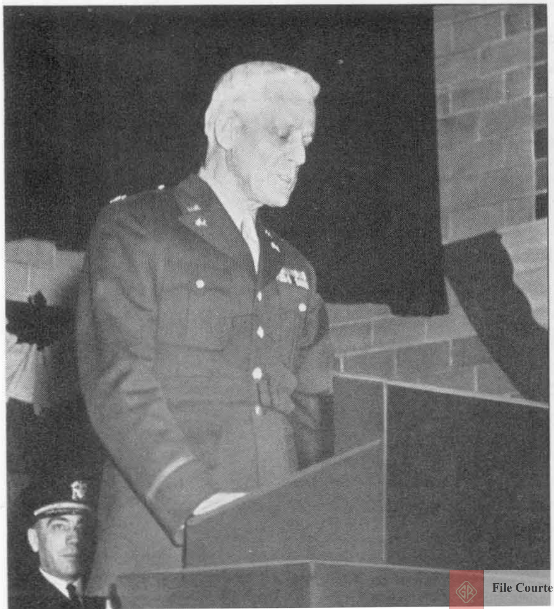
Colonel James H. Van Horn, U.S.A., Signal Officer for the First Service Command, presented "E" pins to a group headed by Charles H. Riemer, President of the General Radio Mutual Benefit Association.

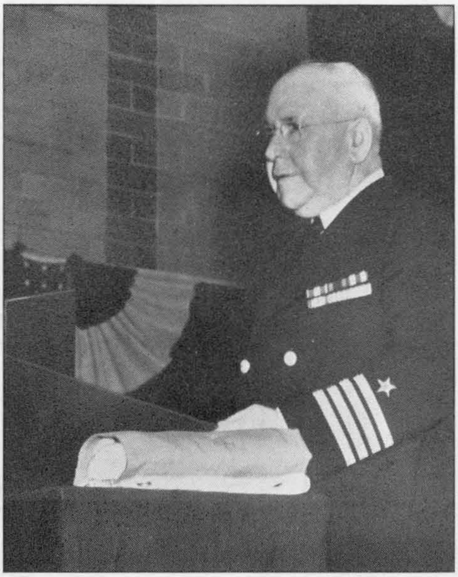
Left to right: Mayor Corcoran, Captain Hyland, Governor Saltonstall, Mr. Riemer, Mr. Eastham, Colonel Van Horn

(*Right*) **Captain Hyland**: "Without these instruments, vitally necessary in the calibration of all types of radio apparatus both at sea and on shore; without the instruments produced by your firm so necessary in the measurement of noises, of vibration on board ships and for many other uses, the efficiency of the fighting ships would be greatly reduced and the machinery, guns and fire control apparatus would not operate at the maximum efficiency for which they were designed."



(*Below*) **Colonel Van Horn**: "And let me point out that, without such equipment, effective joint action of the Army and Navy would be impracticable. This equipment is of utmost importance in establishing communications throughout our armed forces where tactical co-ordination is the essence of combat success."





(*Left*) **Mr. Richmond**: "We have taken for our task the manufacture, and in many cases the design, of electronic equipment not generally available to our Government from other sources, and in many cases in quantities too small, and too difficult in technological design, to interest most manufacturing companies."

(*Above*) **Mr. Riemer**: "We are tremendously proud of the part our Company and apparatus are playing in this war. That pride, however, is tempered in the cooling waters of responsibility and obligation, for we conceive it an obligation to supply in quality and quantity — on time — sufficient instruments to shorten the war."

THE NOISE PRIMER

PART V — PRACTICAL APPLICATION OF THE SOUND-LEVEL METER

● **MANY DETAILS** of the operation of sound-level meters are ordinarily overlooked in both instruction books and theoretical discussions. This chapter is an attempt to answer some of the questions most frequently asked in correspondence and which have not already been mentioned in previous chapters.

Acoustic Conditions for Measurements

Part III described the procedure for correcting sound measurements for background noise level. In Part IV microphone placement was discussed. Another important factor that should not be overlooked is the acoustic condition of the room or space in which the measurements are made. Sound, like light, is reflected by some surfaces and absorbed by others. A porous, soft material or heavy fabric will absorb sound much as a black surface absorbs light. Similarly, a hard surface reflects sound as a white surface reflects light. A source of sound in a room may be likened to a source of light. The sound meter measures the sound pressure at any point just as a photoelectric exposure meter measures the light.

To complete the analogy, since sound-level meters have non-directional microphones, it should be assumed that the photoelectric cell of the exposure meter responds equally to light coming from all directions.

The reading of the exposure meter at any point in the room will depend not merely upon the intensity of the light source, but also upon the absorbing capacity of the walls. With completely flat, black walls the only light reaching the exposure meter will be direct from the lamp. With any other kind of walls the actual reading of the exposure meter will depend upon the reflection from the walls as well as the brightness of the lamp.

"Dead" Room Measurements

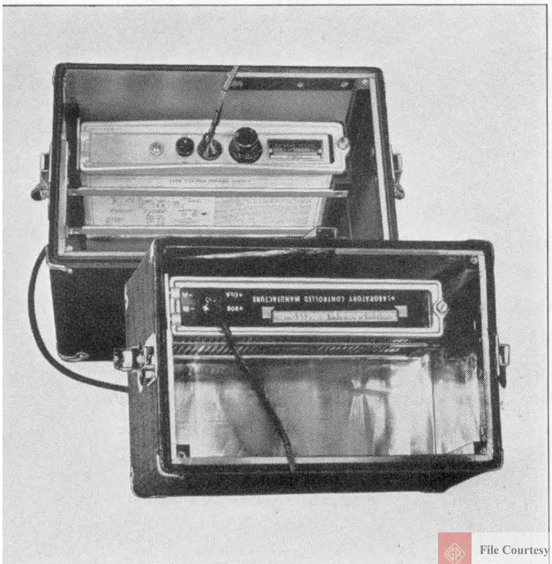
Exactly the same is true in sound measurements. Hence such measurements, so far as possible, are generally made under conditions of high acoustic absorption in order to avoid additional errors resulting from reflections. Reflections are entirely absent only when measurements are made outdoors at some distance from all buildings or other obstructions, or in a room, all interior surfaces of which are 100% absorbent. As a practical matter, such ideal locations are seldom available. For some types of measurements they are not absolutely necessary, and in others it is possible to minimize the effects of those reflections which cannot be avoided.

Radiation of Sound

Sound radiated from a small source varies in pressure inversely as the distance from the source. Hence, each time the distance between the sound meter and the sound source is doubled, the reading of the meter will decrease 6 db if no reflections are present. As a practical matter, the sound pressure around an average machine will pass through several minima and maxima as the sound meter is moved away, and then approach the inverse characteristic — that is, will decrease 6 db each time the distance is doubled, providing reflections are not present. This provides a convenient check on whether or not the surroundings are sufficiently non-reflective. Care should be taken in making this test that the background noise does not introduce serious error. This can be checked by turning off the machine under test and noting the reading of the sound meter on background noise alone. If the background noise is louder than 10 db below the machine noise, correction should be made for it.[11]

It is not always possible, particularly with large machines and small rooms, to obtain high absorption, or even to check absorption by the inverse law, as mentioned above. However, the effects of reflection can be minimized by making measurements fairly close to the machine, so that the ratio of direct sound to reflected sound is high. It is quite general, therefore, in checking large machinery to make an appreciable number of measurements at a relatively small distance and average them.

FIGURE 8. Both the TYPE 759-P50 Power Supply Unit and the Burgess type 6TA60 battery may be used interchangeably in the TYPE 759-B Sound-Level Meter, as shown here.



"Live" Room Measurements

In any room the average sound level will build up to an intensity such that the sound energy absorbed equals the sound energy radiated by the source. Hence in a "live" room — that is, one with high reflecting interior surfaces — the sound will build up to a very high level. This is obviously undesirable for ordinary measurements, but in certain applications it is a real advantage. If such a room has irregular or non-parallel wall surfaces, the level at any point is the result of multiple reflections of sound which originated from all sides of the machine under test. Hence the reading represents, in effect, an integration of the total sound radiated by the machine. The "live" room, therefore, may be very useful for *comparative* measurements, as when quieting a particular machine, since a single sound-meter reading taken at a distance from the machine may be used instead of the average of a large number of readings.

Production Testing

As a practical matter, in the production testing of equipment for noise level, it is seldom possible to obtain ideal acoustic conditions. Tests must generally be made under normal plant conditions of noise and acoustic reflection, and, as a matter of economy, must generally be limited to a few simple measurements.

If the machine under test is fairly noisy and the background noise level at least 10 db lower, it is usually satisfactory to make one or two measurements on each machine at points near the machine which experience has shown provide good indications of the general noise radiated by the machine. This means that, in general, the measurements will be made at the points of maximum noise around the machine and these measurements correlated with

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[11] See Figure 5 (February, 1943, *Experimenter*).

data taken on a few similar machines under more nearly ideal conditions.

A-C Power Supply

Where sound-measuring equipment is operating continuously, as in production testing, portability is not necessary, and batteries are undesirable because of the need for frequent replacement. Under these conditions use of a TYPE 759-P50 Power Supply Unit is recommended with either the TYPE 759-A or -B Sound-Level Meter.[12]

Vibration Pickup

When measuring fairly quiet devices, such as, for instance, electric clocks or speedometers, ordinary plant noise often makes acoustic measurements impractical unless special soundproof booths, etc., are constructed. In many such cases a vibration pickup may be used in place of the microphone. Sound measurements made under satisfactory acoustic conditions can be correlated with the vibration measurements on any particular type of machine and the vibration measurements then used in actual production testing under plant conditions. In this application the vibration pickup is merely used as a comparison device. Vibration pickups will be discussed in more detail in a later chapter.

Extension Cable

When the TYPE 759-A Sound-Level Meter was first announced in 1936, theorists suggested that the microphone mounting on the instrument would be a source of serious error. Previously, most sound-level meters had had the microphones on long cables. Theoretically, the presence of any object in the field around the microphone will distort the field somewhat and cause reflections which will affect the meter readings. As a practical matter, however, on the TYPE 759-A and -B Sound-Level Meters the placement of the microphone above the main body of the instrument is such that the reflection of sounds arriving in a horizontal direction is quite negligible, particularly in the ordinary frequency range of machinery noises. The meter should be used, of course, with the microphone end facing the sound source. The effect of reflections is further reduced in the TYPE 759-B Sound-Level Meter by the microphone design.

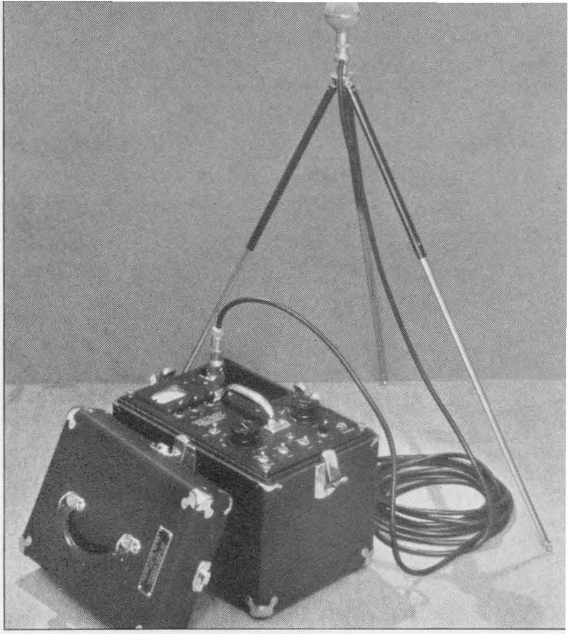

FIGURE 9. TYPE 759-B Sound-Level Meter used with microphone on a tripod.

The practicability of mounting the microphone directly on the sound-level meter is shown by the widespread adoption of this method of mounting by various other manufacturers.

An extension cable for the microphone is sometimes a convenience. For these applications special cables having good shielding and low losses have been developed. Since a crystal microphone is essentially a generator with a capacitive impedance, use of a long cable which is

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[12] This power supply unit allows operation of the TYPE 759-B Sound-Level Meter over its entire range, or the TYPE 759-A Sound-Level Meter over the range down to 34 decibels. The power supply unit fits into the battery compartment of the sound-level meter. The power supply unit is completely described in the January, 1942, issue of the General Radio *Experimenter*.

in effect a capacitive load on the microphone results in a slight reduction in output. A cable correction is accordingly supplied, which should be added to sound-meter readings. The correction is not affected by frequency.[13]

Temperature and Humidity

Most sound measurements are made at normal room temperatures — that is, in the range from 60° to 80°F., but there are some instances where measurements must be made at abnormally high or low temperatures. Definite information regarding the temperature characteristics of microphones is generally lacking, since, as previously pointed out, the microphones were intended primarily for broadcast recording and sim[illegible]es, and variations which would be s[illegible] in noise measurements are of little importance in such work.

The microphone used on the Type 759-B Sound-Level Meter is of the piezo-electric type, utilizing a "bimorph" crystal, which is really two crystals cemented together in such a way that most of the temperature characteristics cancel out. Over the range from 24° to 115° Fahrenheit, cartridges of this type generate a substantially constant voltage at all frequencies up to 2000 cycles. Above this frequency there is some variation amounting to a maximum of ±0.5 db at 3000 cycles and ±1.5 db at 8000 cycles. These variations are well within the normal tolerances on microphones and are unimportant over the frequency range generally encountered in noise measurements.

The characteristic of a crystal microphone which changes most with temperature is its capacitance. The curve shown in Figure 10a shows the average capacitance of a microphone as used on the Type 759-B Sound-Level Meter as a function of temperature.

Cable Correction

So long as the microphone operates into a high impedance, this change in capacitance with temperature has little effect upon the output but, as the load on the microphone decreases in impedance, variations due to the internal capacitance of the microphone become more important. The Type 759-P21 Cable[14] is normally supplied with an attached celluloid tag, as shown in Figure 10b, giving proper corrections for different operating temperatures. This cable is 25 feet long and has a capacitance of 675 micromicrofarads. The correction for operating into other capacitances can be figured from the following formula:

$$\text{db} = 20 \log \left(1 + \frac{C_1}{C_2}\right) \qquad (3)$$

where C_1 is the capacitance of the cable and C_2 is the capacitance of the microphone at the particular temperature. For most practical purposes this can be read directly from Figure 10a. The correction does not change with frequency so long as any shunting resistance remains relatively high. The input resistance of the Type 759-B Sound-Level Meter is approximately 7 megohms.

The crystal units used in these microphones are coated with a moisture-proof compound, and consequently are unaffected by humidity. As with all Rochelle salt devices, the microphone should not be subjected to temperatures higher than 130° Fahrenheit, or permanent damage to the crystal may result.

Variable Sounds

The panel meter on standard sound-level meters such as the Type 759-B

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[13] With the Type 759-B Sound-Level Meter and the Type 759-P21 Cable the correction at average temperatures is 2.5 db. With the Type 759-A Sound-Level Meter and the Type 759-P1 Cable the correction is 1.8 db.

[14] Owing to the shortage of critical materials, this cable is temporarily not available. The correction for any other cable can be computed from Equation (3).

(and Type 759-A) has definite ballistic characteristics, as specified by the American Standards Association. These standards presumably represent an attempt to obtain a reasonable compromise between the response of the ear to varying or transient sounds and what can be obtained in a practical indicating instrument. It is often desirable, however, to obtain a single reading representing an average sound level by means of a heavily damped meter, and for this reason the Type 759-B Sound-Level Meter (and some of the later Type 759-A's) is equipped with a slow-fast meter. This is controlled by a switch directly below the meter. The fast position gives the normal A.S.A. characteristic. The slow position provides a heavily damped meter response for averaging varying sounds. On steady sounds the meter will read the same on either position of the switch.

Why Use a Sound-Level Meter Anyway?

This and the preceding chapters have been mainly concerned with the actual practical side of sound-level measurements with no attempt to gloss over the difficulties or possible errors. An instrument can be used most intelligently only when its limitations as well as its advantages are known. It should be realized, however, that the limitations are inherent in the present state of the art and are not caused by cutting corners in the design of the instrument. The Type 759-B Sound-Level Meter, in particular, represents the best compromise among accuracy, convenience, ruggedness and portability which has been devised to date and its low price is an indication of clean-cut design and efficient manufacturing methods rather than of skimping.

Experts all agree that readings of a sound-level meter do not always check with a sound jury's estimate of loudness, for many reasons which seem insuperable by practical means in the present state of the art. This does not, however, mean that a sound-level meter is useless — quite the contrary. In fact, for many purposes the meter's characteristics are more useful than if they followed the ear exactly.

1. The meter gives a definite numerical reading which can be duplicated quickly, and which can be kept as a permanent record.

2. The meter can distinguish slight changes in level imperceptible to the ear. Several small changes, each one unimportant by itself, can add up to a very definite improvement.

3. The meter's readings are unaffected by the many human variables which enter into any sort of loudness estimates.

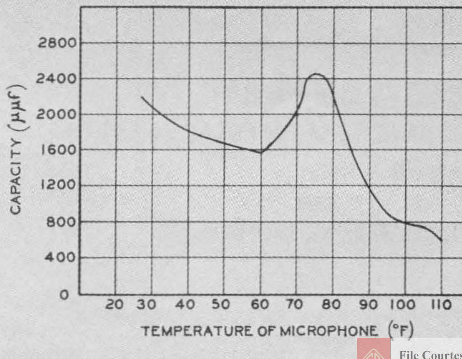

Figure 10 (a). Capacitance variation of microphone of Type 759-B Sound-Level Meter as a function of temperature.

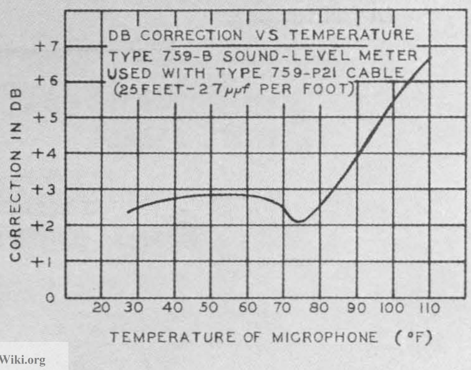

Figure 10 (b). Temperature correction for Type 759-B Sound-Level Meter when used with Type 759-P11 Cable.

4. The meter's frequency characteristic can be adjusted independently of the level.

5. The meter can, for purposes of physical analysis, etc., provide unweighted readings in terms of actual sound pressures.

6. The meter is unprejudiced by likes or dislikes for particular types of sounds.

These are by no means all the advantages of the sound-level meter, but they are most of the important ones. Only through actual use of the meter can an engineer become fully acquainted with its convenience, accuracy, and usefulness. To one who has used a sound-level meter, it is indispensable.

—H. H. Scott

(*To be continued*)

ERRATA

● **THE FOLLOWING ERRORS** have been noted in the February installment of *The Noise Primer*.

Page 2, 1st column, line 5: for 0.002, read 0.0002.

The caption for Figure 6 should read: "Relation between loudness and loudness level. . . ."

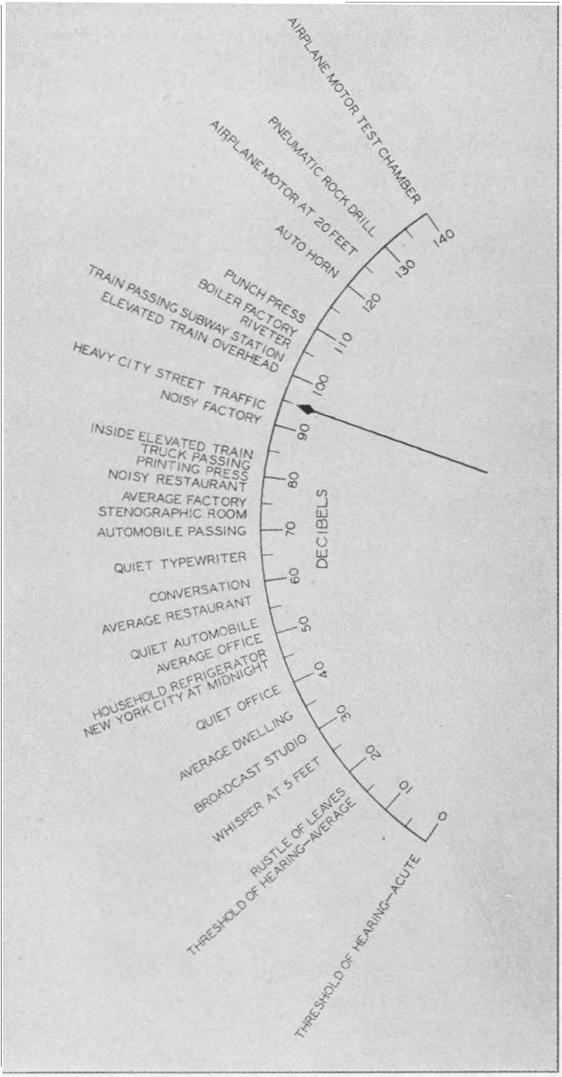

Figure 11. Scale of sound levels for typical noise sources.

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THE General Radio EXPERIMENTER

VOLUME XVII No. 11 APRIL, 1943

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also
IN THIS ISSUE

THE NOISE PRIMER

PART VI
ANALYSIS OF NOISE

Why Analysis?

The sound-level meter measures only weighted or unweighted sound pressure. For a more complete description of the sound, measurements involving pitch and quality are also needed. The usual mathematical concept of a complex sound or vibration is based upon the Fourier system of analysis, which divides any complex waveform into a series of sinusoidal, or pure, waveforms of different pitch or frequency and of definite amplitude and phase relationship. Each of these sinusoidal waveforms contributes to both the loudness and the quality of the sound.

In general, what the ear recognizes as pitch is the frequency of the lowest-frequency sinusoidal component in the complex waveform. The higher-frequency components are generally, but not always, harmonics

FIGURE 12. View of the TYPE 760-A Sound Analyzer with cover removed.

(that is, integral multiples) of this frequency, and determine the quality or timbre of the sound.

For instance, steady-state notes of the same pitch, but played upon different musical instruments, have the same fundamental frequency and differ only in their harmonic structure or overtones. Similarly, two noises of the same intensity and the same pitch may vary appreciably in the annoyance they cause because of different harmonic makeup or "quality."

A sound analyzer measures the amplitude of each individual frequency component.[15] For steady-state sounds, therefore, measurement of level with the sound-level meter and analysis of harmonic structure with the sound analyzer give a substantially complete description of the sound itself. There are other characteristics which may affect slightly the quality of a sound, but for general purposes it may be said that two steady-state noises of the same level and harmonic structure will sound alike.

The analyzer shows clearly why different kinds of musical instruments playing the same note do not sound alike. Each has its characteristic timbre, which depends upon the resonances of the instrument itself.

Similarly, the noise generated by any mechanical device depends upon its own resonances. The sound produced by a machine includes not only a fundamental frequency, depending generally upon the machine's speed, but also many other components of higher frequencies, usually determined by the various resonant frequencies of the machine parts and structural elements. Many of these resonances are calculable[16] or measurable by various methods. Hence an analysis of the noise will provide many clues to the source of the various components. When the source of the noise is found, the problem is half solved. Often relatively simple modifications will entirely eliminate the noise.

Therefore a sound analysis is useful for two important reasons. In the first place, it provides definite information, which can be recorded for later reference, as to the makeup of the sound. In the second place, the sources of the sound can be identified through their corresponding frequency components, so that definite steps can be taken to reduce the sound through proper redesign of the mechanism.

Classification of Noises

Machinery noises may be divided roughly into two classes. The first includes the fundamental frequency at which the machine is operating and various harmonics thereof, as well as any other components which vary in frequency proportionally with the fundamental. Sounds of this class are generally characterized by the harmonic relationship between the various components and are characteristic of most types of rotating or reciprocating mechanisms, particularly those operating at high speeds. These are the noises commonly referred to as "pitched."

The second class of noises contains those components which are *not* definitely related in frequency to the fundamental speed of the machine. These vibrations are generally caused by shock excitation at the machine fundamental speed or some harmonic of it. They produce a series of damped waves whose components correspond to the natural frequency or harmonics of the vibrating

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[15] Except under unusual conditions the phase of the components does not affect the ear and hence is unimportant for purposes of noise measurement.

[16] For instance, see J. P. Den Hartog, "Mechanical Vibrations," published by McGraw-Hill, 1940; S. Timoshenko, "Vibration Problems in Engineering," Van Nostrand, 1937; I. B. Crandall, "Theory of Vibrating Systems and Sound," Van Nostrand, 1926.

parts, rather than to the machine speed or its harmonics.

The actual frequencies involved in such sounds are seldom clearly defined, since the effects of shock excitation, the natural damping of mechanical parts, the movement of the parts, and the variation of forces impressed upon them cause appreciable frequency variations. Such sounds are commonly referred to as "unpitched" and include rattles, buzzes, and similar noises. Their sound energy is generally spread over bands of frequencies rather than being confined to discrete frequencies.

The noise of most machines contains both pitched and unpitched components, but usually most of the important sound energy falls into one class or the other. For example, the whine of a dynamo is almost entirely a pitched sound in Class 1. A typewriter, on the other hand, produces noise almost entirely through shock excitation, and hence this noise is an unpitched sound, falling into Class 2.

Unpitched sounds, except in those few cases such as the typewriter, are characteristic mainly of machines which are poorly designed or in poor repair. The presence of strong Class 2 components in the noise produced by a machine to which they are not characteristic is generally an indication of trouble.

Analyzer Characteristics

It is well known that the ease with which a frequency-selective electric circuit can be adjusted to resonance with any particular signal component depends upon the steadiness of pitch of that component. Fluctuation, or frequency modulation, of the pitch beyond the band width of the selective circuit produces an attenuation of the response dependent upon the type and extent of the frequency modulation and upon the characteristics of the selective circuit.[17]

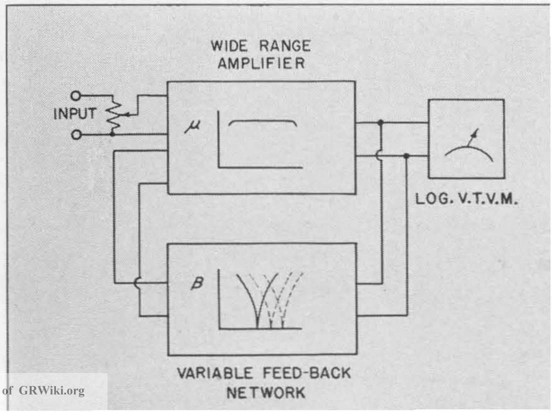

FIGURE 13. Functional block diagram showing the operation of the TYPE 760-A Sound Analyzer. It consists of a high gain amplifier and a frequency-selective feedback network, so designed that the feedback is degenerative at all frequencies except that to which the network is tuned.

Most users of sound-measuring and -analyzing equipment are in agreement that in the ideal noise analyzer the band width of the selectivity curve should be proportional to the frequency to which the device is tuned. For Class 1 sounds this will provide the minimum error, since any attenuation caused by frequency modulation of the sound will be equal for all components, and they will then be measured in their true relative proportions.

For Class 2 sounds it is obviously more difficult to determine the ideal selectivity characteristic, but the constant-percentage type, which widens out in band width proportionally as the frequency is increased, is far more suitable for measuring the unpitched components than an analyzer with razor-sharp selectivity in the high-frequency region. The degenerative type of sound analyzer which has inherently a constant-percen-

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[17] From the mathematical standpoint, frequency modulation produces side bands, just as amplitude modulation does. In frequency modulation strong side bands cover a band width equal to the total frequency swing. These side bands, however, are spaced apart in the frequency spectrum by intervals equal to the modulation frequency, which in machinery sound and vibration problems is generally very low, so that the side bands cannot be measured separately with any practical analyzer now available.

tage band width characteristic,[18] has been developed for noise analysis and is generally better adapted for that purpose than the many modifications of heterodyne and other types of analyzers which are also in use. Figure 13 shows the principle of operation of the degenerative-type analyzer.

The General Radio Type 760-A Sound Analyzer[19] is of the degenerative type and, because of its unusual circuit, it is both inexpensive and easily portable. Because of the absence of inductances in the design of this instrument and the complete electrostatic shielding of the case, this instrument is quite unaffected by ordinary electromagnetic and electrostatic fields.

Where a heterodyne-type analyzer, such as the General Radio Type 736-A is available, it also can be used for noise analysis of sounds where the pitch is constant and no important unpitched components are present. Where new equipment is to be purchased, however, the Type 760-A Noise Analyzer is recommended because of its greater general usefulness and the lesser possibility of error.

The following instructions apply to the Type 760-A Noise Analyzer.

PART VII—HOW TO USE THE SOUND ANALYZER

Relative Readings

The Type 760-A Noise Analyzer is completely self-contained and operated from dry batteries. No battery adjustments are required. Push buttons and a neon lamp on the panel indicate whether or not the batteries have sufficient voltage for satisfactory operation. Complete instructions covering testing and replacement of the batteries will be found in the cover of the instrument.

The analyzer is tuned by means of the large knob and the row of push buttons beneath it. The buttons select the particular frequency range and the knob provides tuning over that range. The calibration is direct reading in cycles per second and may be converted to rpm by multiplying by 60.

To analyze a sound, connect the input of the analyzer to the output of the sound-level meter by means of the cord

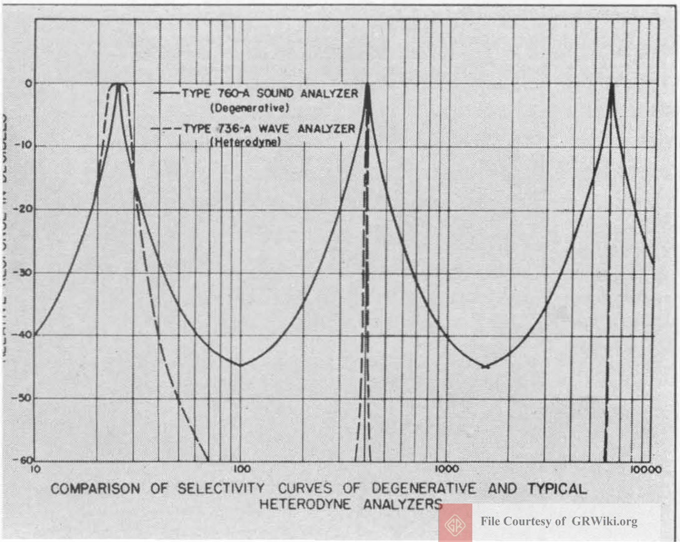

Figure 14. Comparison of the selectivity curves of a degenerative and a heterodyne analyzer. The degenerative analyzer, because of its constant percentage selectivity, is to be preferred for noise analysis.

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[18] The theory of this circuit was described in "A New Type of Selective Circuit and Some Applications," by H. H. Scott, Proc. I.R.E., Vol. 26, No. 2, February, 1938.

[19] This analyzer was described in "The Degenerative Sound Analyzer" by H. H. Scott, The Journal of the Acoustical Society of America, Vol. 11, No. 2, October, 1939; also "An Analyzer for Noise Measurement," *General Radio Experimenter*, February, 1939.

provided. Both instruments should be turned on. The level of the sound which strikes the microphone will be indicated directly on the meter on the panel of the sound-level meter. This reading is the total sound pressure. Press Button A on the sound analyzer, which selects the 25-to-75-cycle range, and turn the main dial slowly from 25 to 75 cycles, noting the deflections of the meter on the sound analyzer. Repeat this process, covering the entire range of the instrument by successively depressing Buttons B, C, D, and E and turning the dial around. The instrument is so constructed that the dial may be rotated continuously in one direction, thus facilitating rapid scanning of the entire frequency range.

During this process the sensitivity control of the analyzer should be turned down whenever a component is found which deflects the meter above the 100% (0 db) point, so that the meter reads exactly at this point. This sets the sensitivity such that the analyzer will read 100% on the loudest component in the sound. *Do not change the setting of this control before the analysis is completed.* The analyzer should then be carefully tuned for maximum amplitude on each component (without touching the sensitivity control) and the results recorded. This provides an analysis directly in terms of the loudest component, which is generally, but not always, the fundamental.

The sensitivity control on the analyzer is intended only for use in making the initial setting and it should not be used as a multiplier for the meter or to extend the scale of the meter

The vacuum-tube voltmeter circuit is so arranged as to provide a semi-logarithmic scale characteristic, in order that components varying in amplitude over a range exceeding 40 db may be read directly from the scale, and with an accuracy proportional to the importance of the components. That is, the strongest components are read with the highest degree of accuracy. The meter is equipped with two scales, one in decibels and one in percentage of full scale, so that measurements may be made in whatever units are most convenient to the operator. The accuracy of the voltmeter calibration is maintained by means of a neon ballast tube.

The analyzer is equipped with an output jack for operating a pair of phones, thus allowing the user to listen directly to the particular component being measured. The semi-logarithmic characteristic of the tube voltmeter circuit provides an automatic volume control effect at the phones output jack, thus avoiding the possibility of acoustic shock to the operator.[20]

Absolute Readings

Relative readings are generally sufficient for practical analyses, but if it is desired to have the readings in terms of the absolute sound level rather than referred to the strongest component, proceed as follows:

Plug the sound-level meter into an alternating-current power line and adjust all controls as when calibrating. This will provide a deflection on the indicating meter of approximately +5.

Connect the analyzer to the sound-level meter, tune the analyzer to the power-line frequency and adjust the SENSITIVITY control so that the indicating meter on the analyzer reads 10 db lower than that on the sound-level meter. For instance, if the sound meter reads +5 the analyzer meter should read —5. *Do not readjust the SENSITIVITY control further.* The dial may

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[20] Because of these avc characteristics, the output at the phones jack is not a pure sine wave, but it is adequate for all listening purposes.

be marked with a pencil to show the proper setting, if desired.

Disconnect the sound-level meter from the power line and adjust the DECIBELS control of the sound-level meter for normal measurement of the sound with the indicating meter showing a deflection between 0 and 10 (except, of course, for levels below 30 db). The analyzer may then be tuned to each individual component in the normal manner. Do not change the setting of the sensitivity control on the analyzer. The absolute level of each component will be indicated directly by the algebraic sum of the setting of the DECIBELS switch on the sound-level meter and the decibels reading of the indicating meter on the analyzer, plus 10 db. The DECIBELS switch on the sound-level meter should not be used to increase the deflection of the meter on the analyzer on low amplitude components since this would overload the output circuits of the sound-level meter and cause distortion.

Choice of Network

Before making an analysis one decision must be made. Which is desired—a measurement of the amount which each component contributes to the sound as heard by the ear, or a direct physical measurement of the relative intensity of each component? If the first is desired, the same weighting curve should be used as when measuring the noise with the meter alone. If a direct physical measurement is desired, however, the C curve (flat) should always be used.

—H. H. Scott

(To be continued)

METHODS OF OBTAINING LOW DISTORTIONS AT HIGH MODULATION LEVELS

● **UNDISTORTED SIGNALS** at high modulation levels are sometimes quite useful in the laboratory for testing purposes, but distortionless output is not easily obtained from low-powered testing equipment. In general, these devices tend to produce appreciable distortion when operated at high modulation levels.

With standard-signal generators, there are two convenient methods by means of which low distortion at high modulation levels can be obtained. These are described below, together with their application to the Type 805-A Standard-Signal Generator.

(a) Carrier Amplitude Reduction

If a modulated r-f voltage be combined in the proper manner with an unmodulated r-f voltage of the same carrier frequency but of opposite phase, the resultant output will have a higher percentage modulation and lower amplitude than the original. Thus it may be seen that, starting with a source of modulated carrier-frequency voltage of relatively low modulation distortion, and reducing the amplitude of the carrier component, it is possible to increase the percentage modulation with no increase in modulation distortion.

When the Type 805-A Standard-Signal Generator is operated at 50% modulation, the modulation distortion is very small. Using this instrument as a source of modulated carrier frequency, it is merely necessary to provide two linear r-f amplifiers and to operate their output circuits in parallel and 180 degrees out of phase. Since it is necessary to obtain unmodulated r-f voltage from the signal generator, one of the linear r-f amplifiers must be directly coupled to the r-f oscillator in the Type 805-A, but through an isolating impedance (Z_1) in order to avoid reaction on the oscillator frequency. The second r-f amplifier may be connected directly to the output terminals of the signal generator. This system is shown in schematic form at the lower right of Figure 1.

There are several precautions to be observed if satisfactory results are to be obtained with this system. The two r-f amplifiers should be identical in construction and have very nearly the same phase shift. Because exact phase balance cannot be conveniently obtained unless a variable element is introduced into one of the r-f amplifiers, some such means of adjustment should be provided. Control of the amplitude of either or both amplifiers provides a means of adjusting the percentage modulation at the output of the system. It is also quite important to isolate the two r-f amplifiers to prevent cross-modulation between them, which would tend to introduce distortion and, under certain conditions, would prevent a symmetrically modulated wave from being obtained. The inability to adjust the modulation to 100%, without clipping negative modulation peaks, is another indication of trouble of this sort.

Further circuit precautions involve the use of a voltage-regulated supply, especially on those units which do not have internally regulated power supplies. This has been found necessary in order that the voltage and phase balance of the system be maintained within the degree of accuracy required.

A suitable means for determining the exact percentage modulation level when operating in the vicinity of 100% is desirable. Any of the conventional methods employing a cathode-ray oscillograph could be used. It is quite difficult to determine, with any degree of accuracy, the exact point at which 100% modulation is reached, however, and some form of an indicating meter seems more useful. The Type 726-A Vacuum-Tube Voltmeter has proved to be quite convenient for this purpose. When used in low impedance circuits at voltage levels above 15 volts, the peak-response characteristics of this instrument are excellent.[1]

A Type 805–A Standard-Signal Generator, used as a source of modulated

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[1] The Type 726-A Vacuum-Tube Voltmeter will indicate peak amplitudes of repetitive transients, provided the peak amplitude is maintained for at least .001 of the period. The scale readings should be multiplied by 1.4 to obtain true peak values.

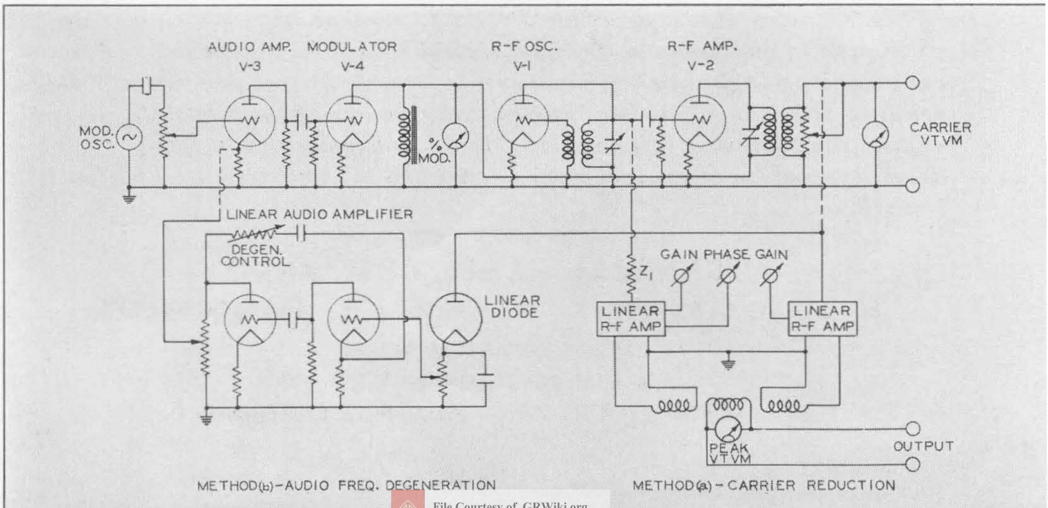

Figure 1. Schematic diagram showing both methods of reducing distortion as applied to the Type 805-A Standard-Signal Generator. The signal generator is shown at the top of the diagram. Below, at the right, is the carrier reduction system; at the left, the audio-frequency degeneration system.

carrier frequency to drive the two amplifiers, has resulted in measurements as low as ½% modulation distortion at 100% modulation. The tests were made at carrier frequencies between 500 and 2000 kc and at modulation frequencies of 50 to 7500 cycles. The instrument was externally modulated, using a Type 608-A Oscillator as a source of audio frequencies of very low distortion.

(b) Audio-Frequency Degeneration

If distortion of the order of 1½% can be tolerated, a considerably simpler method than that described above can be used. This system, which is used in broadcast transmitters, is based on inverse feedback of the modulating frequency as it appears in the envelope of the output voltage. The modulated output of the generator is rectified in a linear detector and the audio-frequency components are then amplified and degeneratively coupled to the internal modulating amplifier of the signal generator. This results in a reduction of both the amplitude and the distortion of the modulation or side-band components. Loss in amplitude may be compensated for by increasing the output from the modulating oscillator.

The arrangement at the lower left of the schematic diagram of Figure 1 shows how this system can be used with the Type 805-A Standard-Signal Generator. In this circuit it is desirable to operate the diode at the maximum voltage obtainable from the instrument. Connecting the diode to the output system, directly ahead of the output control, will work satisfactorily with little or no reaction upon the internal r-f amplifier. Sufficient voltage to operate the diode on the linear portion of its characteristic will be obtained on all but the highest frequency range of the instrument. A suitable non-distorting audio-frequency amplifier should be coupled to the diode and used to provide the necessary feedback voltage. This, for convenience, may consist of a single duo-triode tube. The output of this linear amplifier should be coupled into the cathode circuit of V-3 in the Type 805-A. For proper operation, the linear audio-frequency amplifier should be provided with means of controlling the output amplitude, and the amount of local degeneration, which should be adjusted for minimum distortion. Best results are obtained by modulating the Type 805-A from an external audio oscillator of good waveform, such as the Type 608-A.

—C. A. Cady

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THE General Radio EXPERIMENTER

VOLUME XVII No. 12 MAY, 1943

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also

IN THIS ISSUE

WPB ORDER M-293

● **EFFECTIVE ON MAY 1, 1943,** the War Production Board's General Scheduling Order M-293 went into effect. This Order covers a broad field of what are known as "critical common components" which include many things from jewel bearings to fire extinguishers.

General Radio equipment comes under a general heading of "Test Equipment." This includes nearly all General Radio instruments except Variacs, rheostats, knobs, and dials, and similar parts. The list of material as described in the Order is given on page 2.

Under the terms of the Order the WPB will schedule the deliveries of all of these materials. As a general rule, it is expected that the regular priority system will guide the organization of the shipping schedule. However, the WPB may change it around substantially in order to accommodate the most urgent requirements first.

After May 1 all orders for test equipment as defined by the Order must be accompanied by an approved Form PD-556. This is in effect another version of the old PD-1A. It is an application form which the prospective buyer sends to Radio and Radar Division of WPB for approval. One copy of the form is sent to the supplier with the order. We are prohibited from accepting orders after May 1 that do not have the PD-556 form attached.

IMPORTANT

● **BE SURE** to attach approved WPB Form PD-556 to all orders for instruments after May 1, 1943. Copies of PD-556 and Scheduling Order M-293 may be obtained from your regional War Production Board office.

Send PD-556 to the War Production Board, Radio and Radar Division (Reference: M-293), Washington, D. C., for approval.

This added complication will have at least one very useful result. It will be possible to schedule orders so that the most urgent war needs will be served first, and it does away with the necessity for any kind of priority certification. An approved PD-556 form supplements and replaces every other kind of priority certification that has been heretofore required.

Copies of Order M-293 and of Form PD-556 can be obtained from your local War Production Board.

TEST EQUIPMENT (ELECTRONIC)

AS SPECIFIED IN ORDER M-293

a. Generators of Audio and Radio Frequency Signals, except Rotary Type.

Radio frequency signal generators.
Radio frequency oscillators.
Audio frequency signal generators.
Audio frequency oscillators.

b. Frequency Measuring Equipment, including Standards.

Primary and secondary standards, and associated measuring equipment.
Interpolation oscillators.
Heterodyne detectors.
Audio frequency meters.
Electronic frequency meters.
Electronic deviation meters.
Wavemeters. Wave Analyzers.

c. Waveform Measuring Equipment.

Harmonic analyzers.
Cathode Ray Oscilloscopes.

d. Power Supplies (electronic) and Voltage Regulators.*

e. Impedance, inductance, capacitance, voltage, amperage, and resistance measurement equipment (except instruments controlled by Limitation Order L-203).

Impedance bridges.
Wheatstone Bridges.
Capacitance Bridges.
Precision Condensers.
Vacuum-tube Bridges.
Inductance Bridges.
Megohm Bridges and Megohmmeters.
Vacuum tube voltmeters.
Electronic tube-testers.
Output meters.
Q-Meters.
Electronic Volt Ohmmeters.
Volt Ohm Milliampere Analyzers.
Noise and Field Strength Meters.

f. Precision Standards of items in (e).

g. Electronic Speed Regulating Measuring Equipment.

Electronic Stroboscopic Devices.

h. Electronic Recording Devices, Graphical and Visual.

Oscillograph Recorders.

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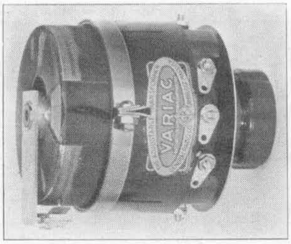
*This does *not* include Variacs.

TYPE 200-B VARIAC



TYPE 200-B Variacs are now shipped assembled for panel mounting, as shown at the left. At present, TYPE 200-B Variacs are available in small quantities on prompt delivery. Priority rating of orders should be AA-3 or better.

THE NOISE PRIMER

PART VIII

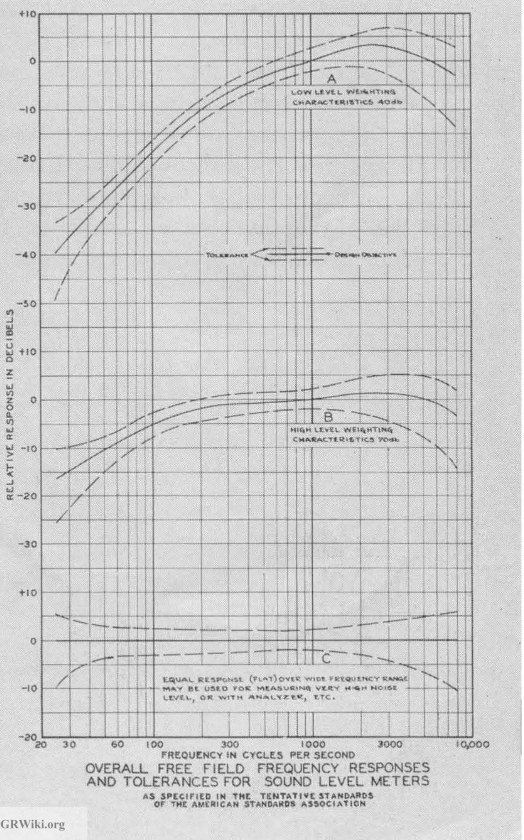
MAXIMUM ACCURACY IN NOISE MEASUREMENTS

● **PREVIOUS CHAPTERS** have covered the theoretical and practical considerations involved in making ordinary sound level measurements and analyses. The instruments used, the Type 759-B Sound-Level Meter and the Type 760-A Sound Analyzer, have been designed in accordance with accepted standards and are direct reading. For the most part, therefore, no auxiliary calibration or correction data are required.

In general, the accuracy of direct-reading measuring equipment can be improved by the use of individual calibration data, and this is particularly true in the case of sound-measuring equipment where, as has been previously pointed out, the microphone characteristic may deviate appreciably from theoretical perfection. This chapter, therefore, is devoted to information which the average user may not need and which is seldom available from manufacturers in published form. The necessary space is being devoted to it here on the theory that the user of instruments should know not only their limitations, but how these limitations may be minimized or overcome in those few cases where it may be necessary.

On average sounds, involving mainly frequencies between 60 and 3000 cycles, different makes and models of sound-level meters meeting the A.S.A. standards will generally read alike within a db or so, which is about all that can be expected in the present stage of microphone development. The degree to which the theoretical response curves must be approximated to meet the A.S.A. requirements was shown by the tolerances in Figure 2.[21] The so-called "noise of general character" for which a sound meter is corrected was shown diagrammatically in Figure 3.

There are, unfortunately, certain individual applications where the sound being measured differs greatly from the general noise of the A.S.A. standards,



OVERALL FREE FIELD FREQUENCY RESPONSES
AND TOLERANCES FOR SOUND LEVEL METERS
AS SPECIFIED IN THE TENTATIVE STANDARDS
OF THE AMERICAN STANDARDS ASSOCIATION

Figure 2. Design objective frequency-response curves between 60 and 8000 cycles for sound-level meters as specified by the American Standards Association (Bulletin Z24.3—1936). These standards do not specify the response below 60 cycles. The extended curves represent present practice as followed by the General Radio Company in the Type 759-B Sound-Level Meter. (As originally printed in Part I, the scale between 30 and 60 cycles was incorrectly drawn. The corrected plot is shown here.)

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[21] January, 1943, *Experimenter.*

and different types of sound-level meters may not read exactly alike. In such cases the question of which meter is most nearly accurate is mainly academic and is liable to lead to unwarranted conclusions since the actual error will depend upon the characteristics of the sound. All microphones of the types commonly used with sound-level meters exhibit marked irregularities in the response curve above 3000 cycles, and some types are also irregular in the low-frequency region. The best procedure, therefore, is to correct for these irregularities, so that the reading will be the same as that which would be obtained by a theoretically perfect, but practically unattainable, sound-level meter — that is, one which followed the design objective curves exactly. This can be done when the response of the equipment at each frequency and the analysis of the sound are definitely known. This requires the use of a calibrated sound-level meter and an analyzer.

A microphone can of course be calibrated with respect to frequency, thus providing a curve showing the response at any frequency throughout its range. A complete calibration covering the whole sound-level meter, including the microphone, can be obtained from the sound-level meter manufacturer[22] or the Bureau of Standards. This provides the user with an exact knowledge of the sensitivity of his meter under a given set of conditions and at definite frequencies. In order to make use of the calibration it is necessary to know also the frequencies of the components which comprise the noise being measured. These may be determined with the sound analyzer. Analyzers, like sound-level meters, do not have perfectly smooth frequency characteristics, but the variations are generally small compared to those of the sound-level meter. However, for use with a calibrated sound-level meter, the analyzer should also be calibrated. This can be done by the manufacturer, or by the user, if he has a good audio-frequency oscillator available.

SOUND-LEVEL METER CALIBRATION

Figure 15 shows a typical sound-level meter calibration as supplied by the General Radio Company. The upper curve represents the over-all acoustical free-field response of the sound-level meter as determined in accordance with the A.S.A. standards, with the weighting switch set at the C position. The relatively smooth frequency response throughout the medium- and low-fre-

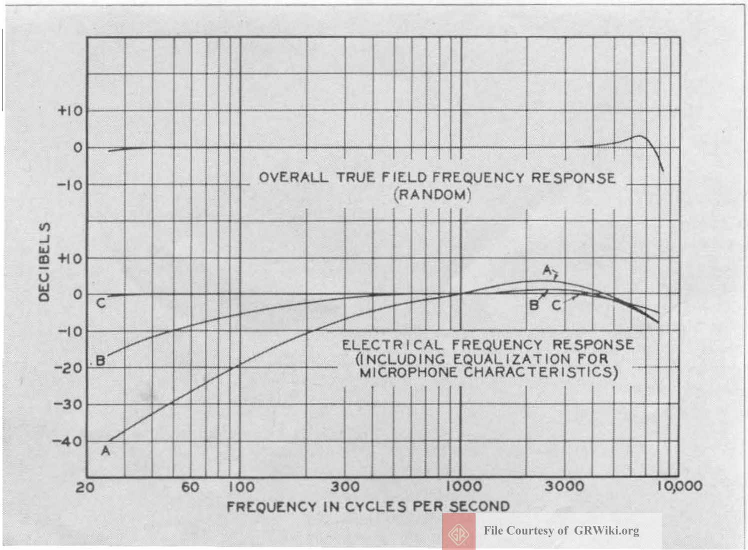

FIGURE 15. Typical average acoustical and electrical calibration curves for TYPE 759-B Sound-Level Meter.

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[22] War conditions have caused temporary discontinuance of the General Radio Company's calibration service. It is expected, however, to be functioning again within a few weeks.

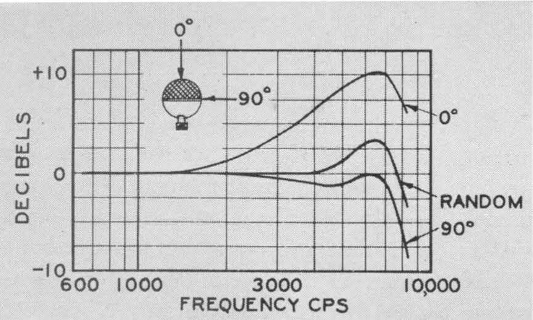

FIGURE 16. Typical curves showing the response of average TYPE 759-B Sound-Level Meters to sounds reaching the microphone at various angles. The random response which corresponds with the A.S.A. Standards represents the over-all characteristic, assuming that the sound arrives equally at all angles in a vertical plane.

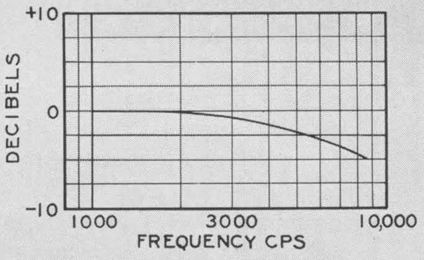

FIGURE 17. According to the A.S.A. Standards, a sound-level meter is calibrated for random response. Under conditions where all of the sound reaches the microphone from the horizontal (90°) direction the above corrections may be applied to the random microphone calibration in order to obtain better accuracy at high frequencies.

quency regions is characteristic of the piezo-electric type of microphone. The lower curves represent the electrical characteristics of the meter, exclusive of the microphone, for the three different weighting curves. These are similar to the curves shown in Figure 2 except for the modifications which are made to compensate for the microphone characteristics. Obviously, additional acoustical curves for the A and B weightings similar to that shown for the C can be plotted from these data, if desired, by merely applying the differences between the three curves for the electrical characteristics to the acoustical C curve.[23]

With all microphone calibrations it should be remembered that the response of the microphone varies somewhat with direction, particularly in a vertical plane. The acoustical curve shown in Figure 15 represents the random response obtained by averaging the characteristics measured at different angles, as specified by the A.S.A. Bureau of Standards calibrations, unless the customer specifies otherwise, are generally made at the so-called 90° angle of incidence (zero degrees is straight down toward the top of the microphone), which corresponds to a sound arriving at the microphone in a horizontal direction. The microphones are normally used in this position, but under practical conditions, as a result either of the size of the sound source or the presence of considerable reflected sound, much of the sound reaches the microphone at angles other than 90°. This is the reason for the A.S.A.'s averaging procedure.

Figure 16 shows the response of a typical TYPE 759-B Sound-Level Meter to sounds reaching the microphone from different directions. All sound-level meters using so-called non-directional microphones will have this general type of characteristic. The response of such microphones is generally symmetrical around a vertical axis. In order to make best use of a calibration curve, therefore, the angle at which the calibration was made should be known. Figure 17 shows the 90° response of a TYPE 759-B Sound-Level Meter microphone in terms of the random response. This curve is typical of this particular type of meter and may

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[23] Bureau of Standards calibrations are plotted in terms of correction rather than actual sensitivity. Hence a Bureau calibration corresponding to the upper curve C in Figure 15 will be inverted. The Bureau does not measure the electrical frequency characteristics as shown in Figure 15, but the *differences* between these electrical curves can generally be obtained sufficiently accurately by taking the *differences* between the design objective curves in Figure 2.

be used for an additional correction where the user is certain that the sound is all reaching the microphone in a horizontal direction. This applies only when the microphone is placed at the same horizontal level as the sound source and the surroundings are substantially non-reflecting, so that only direct sound is reaching the meter.

Caution: It is obvious from Figure 16 that so-called non-directional microphones have unusual sensitivity to high frequencies at the zero degree angle. When measuring sounds involving strong high-frequency components, therefore, care should be taken that the sound strikes the microphone at an angle of 45° or greater, in order to avoid undue influence of these high-frequency components on the total reading. This is ordinarily taken care of automatically, since the microphone is normally used at or near the 90° angle — that is, side on toward the source.

Sounds reaching the microphone by reflection from surrounding objects will arrive at angles other than 90°. So long as this represents a random distribution, the process of averaging used in calibrating the microphone will tend to cancel errors. However, if by any chance some hard surface directly above the microphone reflects or focuses the high frequencies downward onto the microphone, serious errors may result. This possibility of error can be eliminated by covering such surfaces, if present, with felt, carpeting, or other absorbent material. Since only high frequencies are involved, it is a relatively simple matter to absorb them.

It is also possible, in specialized applications where strong high-frequency components are present and where equality of response in all directions in a horizontal plane is not necessary, to use the microphone at the zero degree angle — that is, aimed at the sound source and thus obtain a certain amount of directivity. A special calibration is necessary for this work, however, since the variations in microphone response as the zero-degree angle is approached are sufficiently large to make prediction of the zero-degree response on the basis of the random or 90° response of doubtful value. Figure 16 represents the average of a number of microphones. In any individual microphone the spread between the zero-degree and random reponse curves will vary enough so that the errors involved in applying these average curves would probably be as large as that caused by high-frequency reflections when using the microphone in the usual 90° position.

USING THE CALIBRATED SOUND-LEVEL METER

When the calibrated sound-level meter is used with an analyzer, correction for the microphone characteristic is relatively simple. The noise measurement and analysis should be made in the usual manner. If any of the important sound components occur at frequencies at which the sound meter deviates appreciably from the design objective curve (that is, the acoustical curve C in Figure 15 deviates substantially from a straight line), suitable corrections can be made.

For instance, assume a sound consists almost entirely of a strong component at 7000 cycles. From Figure 15 we find that the meter is 3 db too sensitive at this frequency, and from Figure 18 we find that the analyzer is ½ db low in sensitivity at this frequency. Thus we know that our reading is 2.5 db too high.

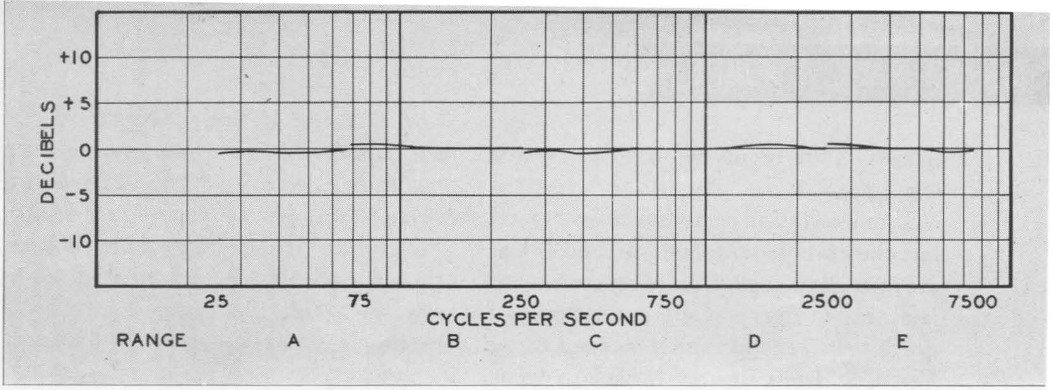

FIGURE 18. Typical response curve of TYPE 760-A Sound Analyzer. A calibration of this type may be made easily by anyone having a satisfactory audio-frequency oscillator and vacuum-tube voltmeter or other indicating device. All that is necessary is to maintain a constant voltage at the input of the analyzer, tune the oscillator to various frequencies throughout the range and at each frequency tune the analyzer to exact resonance and read the indicating meter.

For complex sounds the procedure is somewhat longer, but not complicated. Each component falling at a frequency where the meter calibration shows an appreciable irregularity should then be corrected as described above. Correction will then be

$$\text{db} = 10 \log_{10} \frac{S_2}{S_1} \qquad (4)$$

where S_2 is the sum of the squares of the relative sound pressures of the components, including those *corrected*, and S_1 is the sum of the squares of the relative sound pressures of the components *before correction*.

In general, all components lower than 10% of the loudest may be neglected in computing S_2 and S_1. However, it is important that the same components be used in computing both S_2 and S_1.

Relative sound pressures may be read directly from the percentage scale of the TYPE 760-A Analyzer. When S_2 is smaller than S_1 the correction will be negative, since the actual sound level will be lower than the measured sound level. This correction should be applied to the sound-level meter reading on the particular sound only.[24]

It is also possible, of course, by means of the analyzer to measure the absolute amplitude of each component individually in terms of decibels, convert all of these figures to relative *power* ratios, add them together and convert the sum back to decibels; and the answer should be the same. The first procedure outlined above is generally more accurate, however, since it automatically includes many low-amplitude components or random noise which may not show up in an analysis, but which, when added together, may constitute a measurable part of the total sound energy. It is also somewhat simpler, requiring less calculation.

—H. H. SCOTT

(To be continued)

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[24] This may be read directly from the General Radio Table I by considering $\frac{S_2}{S_1}$ as a power ratio.

SHIPMENT OVERDUE?

The high (or low) point in efficient expediting is reached when the customer calls to chide us about late delivery before we receive the order. A close second is the complaint about delivery when shipment has been made some time earlier, and investigation shows that the material has already been received. Both of these things happen, and more frequently than seems reasonable, even in war time.

Transportation systems are overtaxed, but they are doing a fine job, and delays are usually negligible. Personnel and facilities in every plant are carrying a much heavier load than in normal times. Errors and mix-ups are bound to occur. But we'll all have less trouble if we make sure that we're right before we squawk.

An inquiry about a shipment that has already been received wastes not only your time and ours but that of the transportation company as well, because they trace the thing from shipper to consignee, only to find that it was delivered some days earlier.

At the risk of being caught by our own suppliers in the same practices we deplore in others, we'd like to suggest a couple of rules for the harassed expediter.

1. Be sure the stuff has actually been ordered and the order accepted. As a corollary to this, if it's a repair job you're chasing, be sure you sent us the damaged instrument.

2. If shipment is overdue, check with your receiving department and with the ultimate user in your plant to be sure that the shipment has not been received.

Following these rules will save a lot of telephone calls and a lot of time. Both are valuable in war time.

—H. H. Dawes

SERVICE AND MAINTENANCE NOTES

● **IN THE PAST FEW MONTHS,** Service and Maintenance Notes, not previously available, have been prepared for the following instruments:

Type	*Description*
561–D	Vacuum-Tube Bridge
583–A	Output Power Meter
614–C	Selective Amplifier
616–C & D	Heterodyne Frequency Meter
617–C	Interpolation Oscillator
667–A	Inductance Bridge
676–A	50–Kc Quartz Plate
690–C	Piezo-Electric Oscillator
691–C	Temperature-Control Unit
692–B	Multivibrators
693–B	Syncronometer
694–C	Control Panel
698–A	Duplex Multivibrator
714–A	Amplifier
716–A & B	Capacitance Bridge
723–A, B, C & D	Vacuum-Tube Fork
727–A	Vacuum-Tube Voltmeter
729–A	Megohmmeter
757–A	U-H-F Oscillator
769–A	Square-Wave Generator
805–A	Standard-Signal Generator
913–A	Beat-Frequency Oscillator

Customers who requested the Service and Maintenance Notes for these instruments in previous applications have already received copies. However, if equipment in this list and in our latest catalog has been purchased since January, 1942, and the Notes are not in your files, copies will be mailed upon receipt of the type and serial numbers.

If the binder originally supplied will not accommodate the additional pages, another will be sent upon request to the Service Department.

GENERAL RADIO COMPANY
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BRANCH ENGINEERING OFFICES
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1000 NORTH SEWARD STREET, LOS ANGELES, CALIFORNIA

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THE General Radio EXPERIMENTER

VOLUME XVIII No. 1 JUNE, 1943

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also

IN THIS ISSUE

THE NOISE PRIMER

PART IX

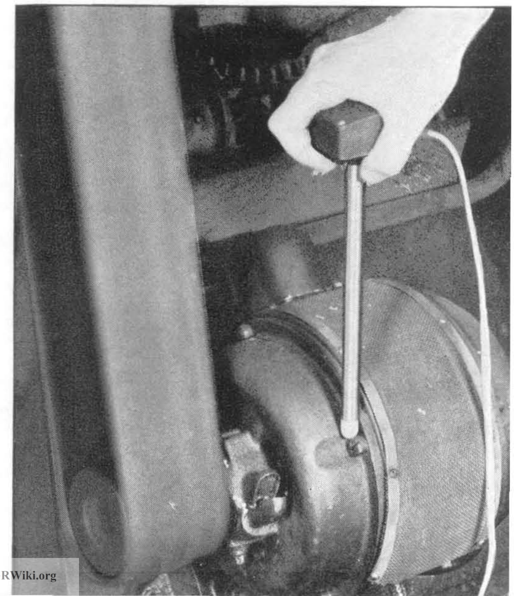
VIBRATION AND SOUND

● **THAT SOUND** and mechanical vibration are related is such a simple concept as to seem hardly worth mentioning. However, the relationships between these two phenomena and, in particular, their effects upon human beings are very complicated indeed.

Most of us use the terms sound and vibration in broad and overlapping senses, but for the purposes of this discussion it is best to keep to rather narrow meanings. Sound, therefore, will be considered as air-borne vibrations of an audible frequency. The term vibration will be used to mean mechanical vibrations or vibrations occurring in solids. The frequency ranges for sound and vibration as thus defined are roughly the same, excepting that important vibrations may also be present considerably below the lower frequency limit of hearing, and satisfactory vibration-measuring equipment must operate at frequencies as low as 2 or 3 cycles per second.

The reasons for measuring or reducing vibration are generally two. In the first place, as is generally realized, audio-frequency vibrations of solids transmit sound vibrations to the air, thus creating noise. The process of quieting a machine or device generally

Figure 19. For most measurements the vibration pickup can be held in the hand.



includes, therefore, a study of the mechanical vibrations involved.

In the second place, serious vibration may cause actual failure which, in the cases of heavy machinery or airplanes, for instance, may have fatal consequences. Vibration, then, is not only a source of noise, but often a source of real danger. The present perfection of high-speed planes, ships, and automobiles could never have been achieved without a thorough study of vibration, its cause, measurement, and cure.

Displacement, Velocity, and Acceleration

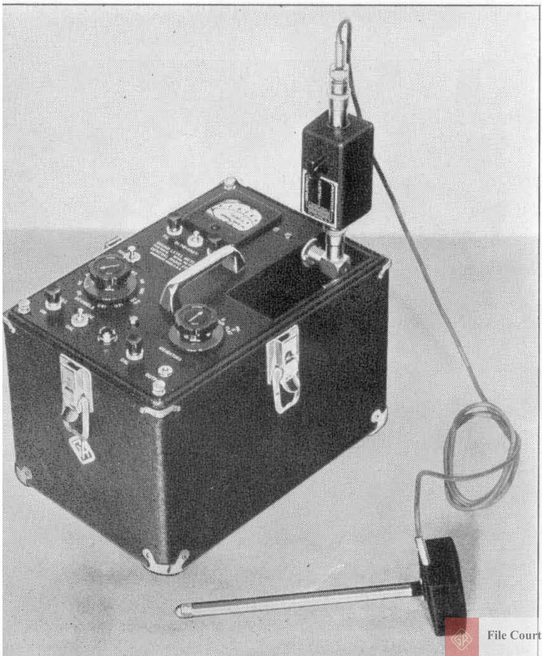
Vibration, like linear and angular motion, can be measured in terms of displacement, velocity, and acceleration. The easiest measurement to understand is that of displacement. In some cases where the displacement is large it can be measured directly with a ruler.

In its simplest case the displacement may be considered as simple harmonic motion, that is, a sinusoidal function having the form

$$x = A \sin \omega t \qquad (5)$$

where A is a constant, ω is 2π times the frequency, and t is the time. The maximum peak-to-peak displacement will be $2A$, and the r-m-s (sometimes loosely spoken of as the average) displacement will be $\frac{1}{\sqrt{2}} A$. The “average double amplitude” (r-m-s) will be $\sqrt{2}A$.

FIGURE 20. The control box and vibration pickup connect to the sound-level meter in place of the microphone.



Displacement, however, is not always the property of the vibration that is required in practical problems. A mechanical part radiating sound may be compared to a loudspeaker. In general the *velocities* of the radiating part (which corresponds to the cone of the speaker) and the air directly next to it will be the same, and, so long as the distance from the front of the part to the back is large compared to one-half of the wavelength of sound in air, the actual sound pressure generated in the air will be proportional to the velocity of the vibration. The sound energy radiated is the product of the velocity squared times the resistive component of the air load. Under these conditions, particularly where noise is important, it is the velocity of the vibrating part and not the displacement which is of greatest importance.

The velocity is the first derivative of the displacement, so that for the simple harmonic vibration in Equation (5) the velocity is

$$v = \frac{dx}{dt} = \omega A \cos \omega t \qquad (6)$$

Thus the velocity is proportional not only to the displacement but also to the frequency of the vibration.

In many cases of mechanical vibration, and particularly where mechanical failure is a consideration, the actual forces set up in the vibrating parts are important factors. Newton's laws of motion state that the acceleration of a given mass is proportional to the applied force, and that this force produces a resulting reacting force which is equal but opposite in direction. Any stresses and strains set up in a vibrating member, therefore, will be proportional to the acceleration of the vibration, which is the second derivative of the displacement. Acceleration measurements are important where vibrations are sufficiently severe to cause actual mechanical failure. Therefore,

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2} = -\omega^2 A \sin \omega t \quad (7)$$

The acceleration, therefore, is proportional to the displacement and to the square of the frequency.

There is another use for acceleration measurements. The analogy cited above concerning the loudspeaker covers the usual case where the cone or baffle is large compared to the wavelength of the sound involved. In most machines this relationship does not hold, since relatively small parts are vibrating at relatively low frequencies. This may be compared to a small loudspeaker without a baffle. At low frequencies the air may be "pumped" back and forth from one side of the cone to the other with a very high velocity, but without building up much of a pressure or radiating much sound energy because of the very low air load, which has a reactive mechanical impedance. Under these conditions the acceleration measurement provides a better measure of the amount of noise radiated than does a velocity measurement.

To summarize, therefore, displacement measurements are used only in those few instances where the actual amplitude of motion of the parts is important. This would include, in particular, those cases where large amplitude of motion might actually cause parts to strike together, thus causing damage or serious rattle. Velocity measurements are generally used in noise problems where the radiating surfaces are comparatively large with respect to the wavelength of the sound. Acceleration measurements are the most practical where actual mechanical failure of the parts involved is of importance, and in most noise problems, particularly those involving small machinery. A vibration meter, therefore, should be able to measure all three vibration characteristics.

The above equations, (5), (6), and (7), represent only sinusoidal vibrations, but, as in the case of complex sound waves, complex periodic vibrations can also be represented as a Fourier series of sinusoidal vibrations. These simple equations may, therefore, be expanded to include as many terms as desirable in order to express any particular type of vibration.[25a] It will be noted that, since velocity is proportional to frequency, and acceleration is proportional to the square of the frequency, the higher frequency components in a vibration are progres-

---

[25a] General equations corresponding to (5), (6), and (7) are, respectively:

$$x = A_1 \sin(\omega_1 t + \alpha_1) + A_2 \sin(2\omega_1 t + \alpha_2) + A_3 \sin(3\omega_1 t + \alpha_3) + \cdots \quad (5a)$$

$$v = \frac{dx}{dt} = \omega_1 A_1 \cos(\omega_1 t + \alpha_1) + 2\omega_1 A_2 \cos(2\omega_1 t + \alpha_2) + 3\omega_1 A_3 \cos(3\omega_1 t + \alpha_3) + \cdots \quad (6a)$$

$$\begin{aligned} a = \frac{dv}{dt} = \frac{d^2x}{dt^2} &= -\omega_1^2 A_1 \sin(\omega_1 t + \alpha_1) - 4\omega_1^2 A_2 \sin(2\omega_1 t + \alpha_2) \\ &\quad - 9\omega_1^2 A_3 \sin(3\omega_1 t + \alpha_3) - \cdots \quad (7a) \end{aligned}$$

where α_1, α_2, α_3, etc., are the relative phase angles of various harmonics and $\omega_1 = 2\pi$ times the fundamental frequency.

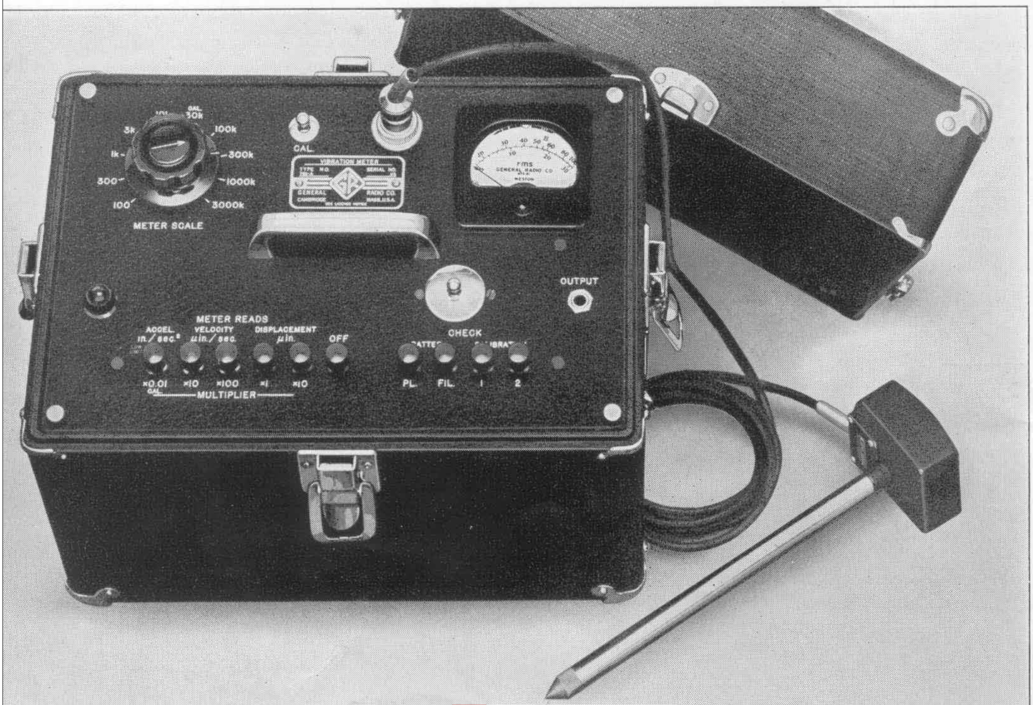
sively more important in velocity and acceleration measurements than in displacement readings. The effective reading of the vibration meter on a complex wave is equal to the square root of the sum of the squares of the components which gives further emphasis to the higher amplitude components.[25b]

PART X—THE VIBRATION METER

Vibration Pickup with the Sound-Level Meter

For some years a vibration pickup has been available as an accessory for the General Radio Sound-Level Meter. The pickup, which responds to mechanical vibrations, is merely substituted for the microphone, and the sound-level meter used otherwise in a normal fashion. With the TYPE 759-B Sound-Level Meter the TYPE 759-P35 Vibration Pickup and the TYPE 759-P36 Control Box are used. The pickup itself is of the inertia-operated piezo-electric type, which responds to acceleration.[26] The control box, which connects between the meter and the pickup, provides electrical integrating circuits. The integrating circuits allow the conversion of this response for read-

FIGURE 21. TYPE 761-A Vibration Meter, designed particularly for machinery vibration problems, covers the frequency range from 2 to 1000 cps (120-60,000 rpm).



[25b] The vibration meter reading of displacement corresponding to (5a) would be

$$|x| = \frac{1}{\sqrt{2}}\sqrt{A_1^2 + A_2^2 + A_3^2 + \dots} \tag{5b}$$

The velocity and acceleration readings would be, respectively

$$|v| = \frac{\omega_1}{\sqrt{2}}\sqrt{A_1^2 + 4A_2^2 + 9A_3^2 + \dots} \tag{6b}$$

$$|a| = \frac{\omega_1^2}{\sqrt{2}}\sqrt{A_1^2 + 16A_2^2 + 81A_3^2 + \dots} \tag{6c}$$

[26] In this type of pickup the crystal is deflected by its own inertia when the pickup is subjected to vibration. The voltage generated is proportional to the actual force exerted on the crystal which is proportional to the acceleration.

ing velocity or displacement. This combination of pickup, control box, and sound-level meter provides a convenient and inexpensive way for owners of sound-level meters to make vibration measurements within the audio-frequency range. However, it should be remembered that the sound-level meter circuits were intended only to respond down to 25 cycles, and consequently this combination is not suitable for measuring lower-frequency vibrations.

Also, the sound-level meter reads in terms of decibels, which must be converted to other units if the readings are to mean anything in terms of vibration amplitude, velocity, or acceleration. A calibration chart is provided with each control box giving the proper correction figures for that pickup and control box when used with a particular sound-level meter. By means of these data plus a decibel table (supplied in the instruction book), the readings may be converted readily to the more logical units of micro-inches, micro-inches per second, or inches per second per second.

The TYPE 761-A Vibration Meter

For low-frequency vibrations, or where a large number of accurate observations must be made with a maximum degree of convenience, an instrument designed particularly for vibration measurements is desirable. The TYPE 761-A Vibration Meter is similar in many respects to the TYPE 759-B Sound-Level Meter. It is mounted in a case of nearly the same size, operates from the same size battery, and has a similar mechanical construction, including the free-floating tube shelf. However, the vibration meter was intended to take full advantage of the maximum frequency range of the piezo-electric type of pickup, which extends smoothly from 2 to 1000 cycles per second. Also, the meter is calibrated directly in terms of the r-m-s displacement, velocity, and acceleration and indicates these, respectively, in micro-inches, micro-inches per second, and inches per second per second.[27]

Since the vibration pickup used with this meter is of the acceleration type, two stages of electrical integration are necessary to provide the various types of response. Because the integrating cir-

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[27] The TYPE 761-A Vibration Meter is completely described in "A General-Purpose Vibration Meter" by H. H. Scott, Journal of the Acoustical Society of America, Vol. XIII, No. 1, pp. 46–50, July, 1941. A brief description is also included in the General Radio *Experimenter*, Vol. XVI, No. 1, pp. 1–8, June, 1941.

FIGURE 22. Electrical frequency response of the TYPE 761-A Vibration Meter showing effects of integrating circuit.

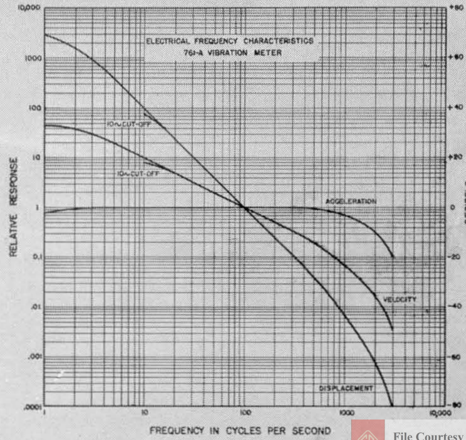
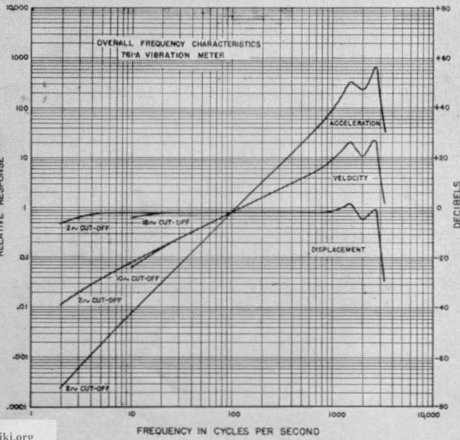


FIGURE 23. Over-all response of the TYPE 761-A Vibration Meter including the vibration pickup.



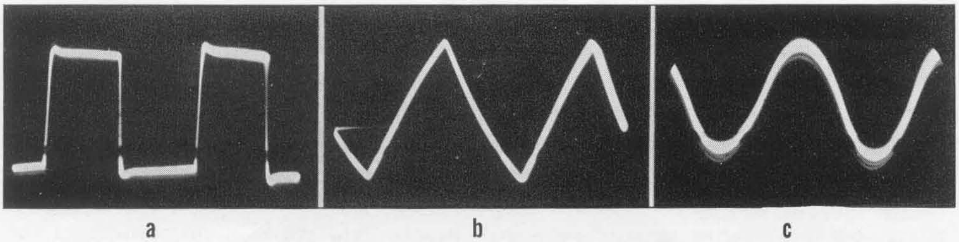


FIGURE 24. Illustrating the operation of the integrating circuits in the vibration meter (a) shows a square wave as transmitted by the amplifier when set for acceleration measurements, (b) shows the wave after one stage of electrical integration for velocity measurements, (c) shows the result of two stages of integration as used for displacement measurements.[28]

cuits are built in as part of the amplifier, better performance is possible than with a control box attachment. Figure 22 shows the electrical frequency characteristics of the vibration meter excluding the pickup. Figure 23 shows the over-all characteristic in terms of relative response for a constant-displacement vibration in terms of frequency. The irregularities above 1000 cycles are due to natural resonances in the pickup, but it will be noted that the average response is actually quite useful to 2000 cycles or higher. These figures show graphically how the integration process attenuates the higher frequencies with respect to the lower frequencies.

Figure 24 shows the actual effect of the electrical integration on a particular waveform. The square waveform of Figure 24a has strong harmonics. After two steps of integration the result in Figure 24c is substantially a sinusoidal waveform.[28]

PART XI — HOW TO USE THE VIBRATION METER

Operating Instructions

Like the sound-level meter, the vibration meter has an instruction sheet fastened in the cover which covers the actual operations involved in adjusting and reading the instrument. A knob marked METER SCALE provides in effect a multiplier for the indicating instrument. The red meter scale should be used with the red positions of the knob and the black scale with the uncolored positions. The reading of the control in all cases represents the full-scale deflection of the meter, so that it is merely necessary to add decimal places to the meter reading.

In addition, there is a row of five push buttons to select acceleration, velocity, and displacement response. For each of the latter two characteristics two but-

---

[28] The waveforms shown in Figure 24 may be represented by the following Fourier series:

$$\text{(a)}\quad a = -\omega_1{}^2 A \sin \omega_1 t - \frac{\omega_1{}^2 A}{3} \sin 3\omega_1 t - \frac{\omega_1{}^2 A}{5} \sin 5\omega_1 t - \cdots$$

$$\text{(b)}\quad v = \int a\,dt = \omega_1 A \cos \omega_1 t + \frac{\omega_1 A}{3^2} \cos 3\omega_1 t + \frac{\omega_1 A}{5^2} \cos 5\omega_1 t + \cdots$$

$$\text{(c)}\quad x = \int v\,dt = \int\int a\,dt = A \sin \omega_1 t + \frac{A}{3^3} \sin 3\omega_1 t + \frac{A}{5^3} \sin 5\omega_1 t + \cdots$$

These correspond, respectively, to Equations 7, 6, and 5, and to Equations 7a, 6a, and 5a in Note 25. Note that for this particular waveform, while the acceleration equation gives 33% third harmonic, the displacement one gives only 3.7%.

tons are provided. The normal buttons are those which provide a low-frequency limit of 2 cycles. The extra buttons, which are so marked, provide a low-frequency limit of 10 cycles, which, however, allows an increase in sensitivity of the meter by a factor of 10 : 1. This is a great advantage for measuring low-amplitude vibrations such as occur, for instance, in clocks, speedometers, and other small mechanisms. Such vibrations seldom have any important components below 10 cycles. Below each button is engraved a multiplying factor (always a multiple of 10) which should be applied to all readings when that particular button is used.

Push buttons are also provided for checking the battery and the calibration.

Sensitivity of Vibration Meter

The TYPE 761-A Vibration Meter will measure displacements as low as 16 micro-inches, velocities as low as 160 micro-inches per second, and accelerations as low as 0.160 inches per second per second.[29]

Pickup Placement

The pickup responds most strongly to vibrations perpendicular to its front surface (the surface with the nameplate). A threaded socket (¼″ — 28th) is provided on this surface so that the pickup may be bolted or clamped in any desired fashion. A conical and a rounded tip are also provided, and a long metal probe, all of which fit the threaded socket. The tips may be fastened directly to the pickup or to the end of the probe. By these means it is generally possible to hold the pickup against a vibrating surface or part so that it will pick up the vibration satisfactorily. Sufficient pressure should be used on the pickup so that it follows the vibration accurately without chattering, but care should be taken not to push so hard as to affect materially the vibration itself. Figure 19 shows how the pickup is normally used with the probe. For accurate reading the pickup should always be held or mounted so that its front surface is perpendicular to the direction of vibration.

Characteristics of Pickup

Like all piezo-electric microphones and pickups, the vibration pickup should not be allowed to reach temperatures above 130° F. or permanent damage may result. Measurements can be made on hotter machinery providing they are made quickly enough so that the pickup does not become heated.

At lower temperatures the temperature characteristics of the pickup are similar to the piezo-electric microphones (see Part V). The actual capacitance of the pickup is approximately 0.005 microfarad. The usual short cable supplied on the pickup does not require a temperature correction, but if a long cable is used the Equation (3) in Part V may be used.[30]

The pickup should not be subjected to accelerations greater than 10 times that of gravity (10g).[31]

Choice of Characteristic

The field of vibration measurement is not as well standardized as that of sound measurements. The choice among dis-

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[29] The displacement and velocity figures are for a low frequency cut-off at 10 cycles. These limits are multiplied by 10 when the full range down to 2 cycles is used.

[30] For this purpose the capacity values in Figure 10(a) may be multiplied by two. Figure 10(b) will also apply if a cable of approximately 1350 $\mu\mu$f is used. These figures are in Part V.

[31] On the calibration of the vibration meter this is equivalent to an acceleration of 3900 inches per second per second, a velocity of $\frac{6.3 \times 10^3}{f}$ micro-inches, or a displacement of $\frac{10^8}{f^2}$ micro-inches, where f is the frequency in cycles per second.

placement, velocity, and acceleration generally depends upon the use for which the data are needed and the considerations mentioned in Part IX. Typical examples of applications for the different types of measurements are as follows: Displacement measurements are widely used in measuring ship vibrations and vibrations in heavy machinery. Velocity measurements are used for measuring sound transmission through walls, the sound radiated by large surfaces such as power transformer shells, etc. Acceleration measurements are used in most machinery noise problems or where parts are liable to fail as a result of the vibration.

In all cases it should be remembered the acceleration measurements give the greatest emphasis to the high frequencies and displacement measurements to the low frequencies.

Applications of the Vibration Meter

All designers of airplanes, ships, and other expensive or elaborate structures, particularly where vibration may be dangerous, carefully calculate the vibratory conditions as a part of the design work.[16] Such calculations, however, generally involve assumptions which cannot always be rigidly justified, and measurements are necessary on the completed structure to check the calculations and make minor readjustments.

In the case of small machinery, it is sometimes more economical to build a sample and measure the vibration than to spend too much time on laborious calculations. The vibration meter, therefore, is not a substitute for thorough theoretical analyses, but should be used to supplement and check such analyses. In many cases its use will greatly simplify the calculations and reduce the number which are necessary.

The vibration meter is also an invaluable tool in checking finished equipment for vibration and, indirectly, for noise, as previously pointed out in Part V. This last application allows noise tests to be carried on under unfavorable conditions of ambient noise level, after correlating noise meter and vibration tests on a few sample machines.

— H. H. Scott

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[16] Note 16 was included in Part VI.

INDEX TO VOLUME XVI AND VOLUME XVII

An index for Volumes XVI and XVII of the Experimenter has been prepared and will be mailed to any reader upon request.

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also
IN THIS ISSUE

THE NOISE PRIMER

PART XII

ANALYSIS OF VIBRATION

● **THE VIBRATION METER** measures the displacement, velocity, or acceleration of a vibration in terms of the r-m-s value of the waveform. Unless the waveform is substantially sinusoidal, however, the vibration meter by itself gives little information about the frequencies involved.[32] An analyzer, therefore, is desirable and in many cases a necessity. As with noise, the analysis of vibration provides clues to the sources of the various components and information necessary in the suppression of the vibration.

The general discussion of analysis and the classification of noises contained in Part VI (April *Experimenter*) applies equally well to vibration and need not be repeated here. Vibration, like noise, may be classified into two types — Class 1, or pitched, which consists mainly of harmonics or subharmonics of a fundamental frequency, all of which

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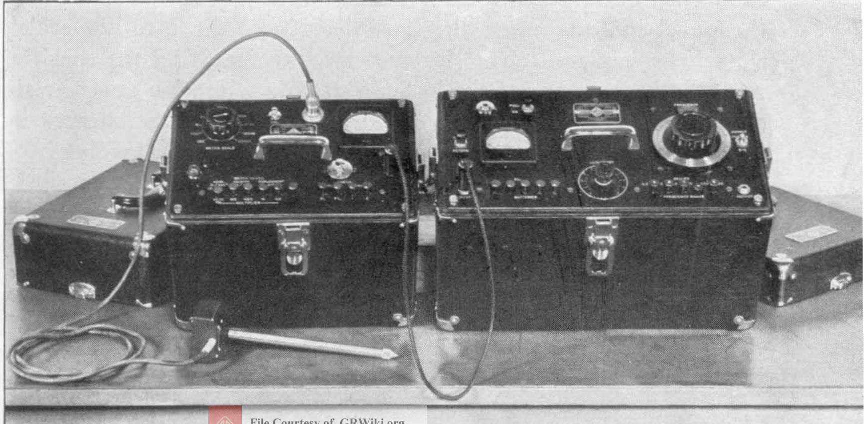
[32] For sinusoidal vibrations, a measure of the frequency may be obtained by taking readings of displacement and velocity. As shown in Equations (5) and (6), the frequency will be: $f = \frac{v}{2\pi x}$. Displacement (x) and velocity (v) readings are better for this sort of frequency measurement than acceleration readings, since they are less affected by any harmonics that may be present in the waveform.

FIGURE 25. The TYPE 762-A Vibration Analyzer was designed particularly for use with the TYPE 761-A Vibration Meter.



will vary in frequency by the same percentage that the machine speed varies; and Class 2, or unpitched, which are caused by shock excitation and occur over bands of frequencies.

Analyzer Characteristics

The degenerative analyzer circuit as used in the TYPE 760-A Sound Analyzer (see Part VI) is even better suited to vibration problems, since its circuit is naturally adapted for use at very low frequencies. This type of analyzer does not require any inductances or transformers in its construction. Hence it is free from the usual difficulties encountered when iron cores are used at low frequencies with attendant distortion and pickup. For use in the frequency range above 25 cycles, the standard TYPE 760-A Sound Analyzer is satisfactory. For vibration problems involving lower frequencies, a special instrument has been developed.

The Type 762-A Vibration Analyzer

The TYPE 762-A Vibration Analyzer[33] covers the frequency range from 2.5 to 750 cycles per second (150 to 45,000 rpm), but otherwise is similar to the sound analyzer. The meter scale on the vibration analyzer is calibrated in linear units for reading displacement, velocity, and acceleration directly in terms of micro-inches, micro-inches per second, and inches per second per second, respectively, rather than decibels, thus matching that on the TYPE 761-A Vibration Meter. The selectivity characteristics are shown in Figure 26. It will be noted that the selectivity curve maintains the important constant shape in terms of percentage of the resonant frequency over the entire range, while operation of a conventional heterodyne analyzer in the low-frequency range becomes completely impractical. The degenerative circuit, so far as is known at the present time, provides the most satisfactory means for obtaining high selectivity at subaudible frequencies.

The general design features of the vibration analyzer are the same as for the sound analyzer.

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[33] This analyzer was described in "An Analyzer for Sub-Audible Frequencies" by H. H. Scott, Journal of the Acoustical Society of America, Vol. XIII, No. 4, pages 360–362, April, 1942.

PART XIII

HOW TO USE THE VIBRATION ANALYZER

Relative Readings

All batteries for operating the vibration analyzer are contained within the case. Push buttons and a neon lamp on the panel indicate when the batteries should be replaced. The instructions mounted in the cover of the instrument should be followed.

Tuning is accomplished by the large knob and the push button range switch. The calibration is direct reading in cycles per second and may be converted to rpm by multiplying by 60.

A cord is provided to connect the input of the analyzer to the output of the vibration meter. For relative readings, the 0-to-120 scale is most convenient, and the sensitivity control on the vibration analyzer should be set so that for the strongest component of the vibration the reading is 100. This should be done with the vibration meter so adjusted that a normal indication is obtained on the indicating meter of that instrument.

The best procedure for setting the sensitivity control of the analyzer is as follows: Press range button A (2.5 to 7.5 cycles) and turn the main analyzer dial slowly, noting the deflections of the meter on the analyzer. Repeat, covering the entire range of the instrument by successively pressing buttons B, C, D, and E, and turning the dial around. The dial may be rotated continuously in one direction.

During this process the SENSITIVITY control on the analyzer should be turned down whenever a component is found which deflects the meter above 100, so that the meter reads 100 exactly. This sets the sensitivity such that the analyzer will read 100% on the strongest component in the vibration. *Do not change the setting of this control before the analysis is completed.*

The analyzer should then be tuned for maximum amplitude on each component (without resetting the sensitivity control) and the results recorded directly in terms of frequency and percentage of the amplitude of the strongest component. The procedure is exactly the same as for the sound analyzer. Because of the natural slow response of highly selective low-frequency circuits, a METER RETURN button is provided. When the operator has tuned the analyzer away from a component, pressing this button will return the meter reading quickly to zero.

The vacuum-tube voltmeter circuit included in the vibration analyzer provides a semilogarithmic scale on the indicating meter, so that the entire usable range of the instrument may be obtained without additional multipliers, etc. The controls of the vibration meter and the SENSITIVITY control of the vibration analyzer should not be readjusted during the analysis.

The analyzer is equipped with an output jack for operating a pair of phones which may be used for listening to the component being measured, if it is of audible frequency.[34]

Absolute Readings

For most purposes, relative readings are sufficient, but absolute readings may also be made with the vibration analyzer if desired. For absolute readings, the calibration procedure is as follows: Connect the vibration meter to the 60-cycle line as when adjusting its calibration. Connect the analyzer to the vibration meter in the normal manner. Depress the button marked CALI-

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[34] Because of the a-v-c characteristics of the vacuum-tube voltmeter circuit, the output applied to the phones is not a pure sinusoid. Hence some output may be heard at very low frequencies which would normally be inaudible.

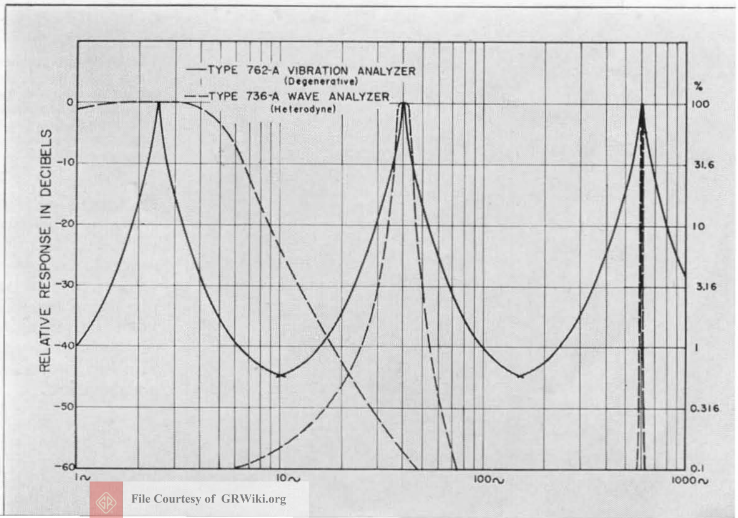

FIGURE 26. Selectivity characteristics of the TYPE 762-A Vibration Analyzer as compared with a typical (TYPE 736-A) heterodyne type of wave analyzer. Of utmost importance is the selectivity curve of the vibration analyzer, which maintains a satisfactory width and shape at both low and high vibration frequencies.

BRATE 1 on the vibration meter and tune the analyzer to maximum response at the power-line frequency. Adjust the analyzer sensitivity control so that the meter on the analyzer reads the same as the one on the vibration meter.[35] It is desirable to mark this calibration point on the sensitivity dial of the analyzer with a pencil so that it can be returned to if the control is accidentally shifted. The control should be left at this point and not readjusted during an analysis.

After the analyzer sensitivity is set, the vibration meter should be disconnected from the power line and adjusted for normal reading on the vibration to be analyzed. The analyzer may then be tuned to the various components of the vibration, the meter of the analyzer being read in exactly the same way as the meter of the vibration meter, using the readings of the METER SCALE knob and the multiplier factors of the push buttons on the vibration meter. The METER SCALE knob on the vibration analyzer also should not be readjusted, but should be left at the setting which gives a deflection on the upper part of the meter scale on that instrument.

The red scale on the analyzer should be used when the METER SCALE knob of the vibration meter is set at a red point and the black scale when the knob is set at an uncolored point. The

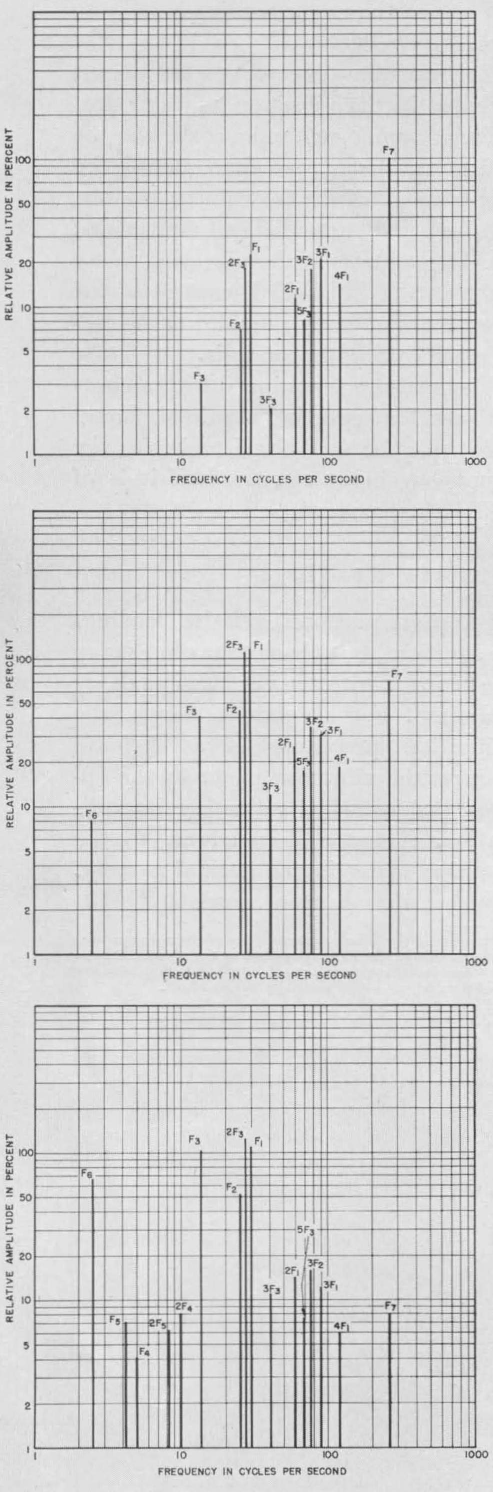

FIGURE 27. Typical analyses of machinery vibration, showing (top) displacement, (center) velocity, and (bottom) acceleration measurements as made on a single machine under the same conditions. These illustrate the complexity of the vibrations which can be analyzed with the vibration analyzer, also the differences in the importance of the various components in measurements of displacement, velocity, and acceleration.

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[35] On recent-production vibration analyzers the red and black scales track the same as on the vibration meter. On earlier models the scales are slightly displaced. With these analyzers two positions of the sensitivity control should be determined, one for the red scale and one for the black, if maximum possible accuracy is desirable. Otherwise an average setting is satisfactory.

analysis will then be in terms of the same absolute values as the vibration meter reading[36] and the same multiplying factors will apply.

Displacement, Velocity, and Acceleration

The analysis will be made in terms of displacement, velocity, or acceleration, depending upon the setting of the vibration meter. Choice among these different characteristics should be based upon the same considerations as when measuring vibration, as described in Part XI.

Figure 27 shows typical machinery vibration analyses as made with the Type 761-A Vibration Meter and the Type 762-A Vibration Analyzer for (a) displacement, (b) velocity, and (c) acceleration. The change in the relative amplitudes of the various components for the different types of measurements will be noted.

The use of the Type 762-A Vibration Analyzer is not limited to the analysis of the output of the Type 761-A Vibration Meter. It can be used with any vibration meter for measuring either linear or torsional vibrations.

* * *

This is the end of The Noise Primer. Whether it has been too long or too short, too technical or too popular are matters we are not in a position to judge. It is hoped at some future date to reprint the series, with whatever modifications may prove desirable, in the form of a booklet to succeed Bulletins 20 and 30 ("The Technique of Noise Measurement" and "The Technique of Noise Analysis," respectively).

If you have any suggestions concerning such a booklet, please write to us. Also, we shall be glad to answer any other questions in regard to the measurement or analysis of noise and vibration, so far as we are able. We do not run a consulting service, neither is it our intention to write a textbook. We are, however, anxious to provide the best information possible to users of our equipment in order that they may secure a maximum benefit from its use. Your suggestions, therefore, are very important.

— H. H. Scott

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[36] Referring to Note 25a (June issue), which gives general equations for Class 1 (pitched) vibrations, the readings of the analyzer on displacement will correspond to $\frac{1}{\sqrt{2}}A_1, \frac{1}{\sqrt{2}}A_2, \frac{1}{\sqrt{2}}A_3$, etc., on velocity to $\frac{1}{\sqrt{2}}\omega_1 A_1, \frac{1}{\sqrt{2}}2\omega_1 A_2, \frac{1}{\sqrt{2}}3\omega_1 A_3$, etc., and on acceleration to $\frac{1}{\sqrt{2}}\omega^2{}_1 A_1, \frac{1}{\sqrt{2}}4\omega^2{}_1 A_2, \frac{1}{\sqrt{2}}9\omega^2{}_1 A_3$, etc. The corresponding total levels indicated by the vibration meter are given in Note 25b. In general, the equations for Class 2 (unpitched) vibrations will be the same, excepting that the components are not necessarily harmonically related.

400-CYCLE OPERATION OF 60-CYCLE INSTRUMENTS

● **THE FLIGHT TESTING** of airplanes often involves a variety of electrical measurements, many of which are not easily handled by an automatic radio recording system. Many standard laboratory measuring instruments, designed for 60-cycle power supply, can be used directly on the 400-cycle supply available in planes. In particular, instruments whose voltage regulating systems are not frequency sensitive, and in which slight increases in background hum are not serious, may give quite satisfactory performance.

A number of General Radio instruments have recently been tested on the

500-cycle power supply available in our laboratories. The results of these tests are listed below.

Type 631-B Strobotac

The operation of this instrument was normal in all respects. However, since the reed provided for checking the calibration is tuned to 60 cycles, it could not be used at the higher frequency. This should not be a serious drawback, because the periods of operation at 400 cycles would presumably be short, and the instrument could be standardized at 60 cycles before and after the test flight.

Type 804-B UHF Signal Generator

The performance obtained was quite satisfactory, although appreciable power supply hum appeared at the r-f output terminals. With the generator unmodulated, however, this should be of no consequence.

Type 620-A Heterodyne Frequency Meter and Calibrator

Except for a noticeable hum in the audio-frequency output, operation was quite satisfactory. The only effect of the increased hum is to reduce the effective sensitivity so that very weak beat tones are not as easily detected.

Type 700-A Beat-Frequency Oscillator

The operation of this instrument was normal, with a barely audible hum in the head telephones connected to the output terminals.

Type 736-A Wave Analyzer and Type 834-B Electronic Frequency Meter

Neither of these instruments could be made to operate properly. They cannot be used at frequencies of the order of 400 or 500 cycles with their present power supply.

INSTRUMENTS DISCONTINUED SINCE THE PUBLICATION OF CATALOG K— 1939 EDITION

● **SINCE THE PUBLICATION OF CATALOG K**, 1939 edition, the items in the following list have been discontinued in order that we might use our facilities more efficiently for the production of items urgently needed for the war effort. Some of these are small items for which no appreciable war demand exists. Others have been made obsolete by advances in the art. Also included are instruments for which satisfactory substitutes can be obtained from other manufacturers.

Type	*Description*
25-A	Frequency Monitor
70	Variacs
80	Variacs
90-B	Variac
138-A	Binding Post
138-D	Switch Contact

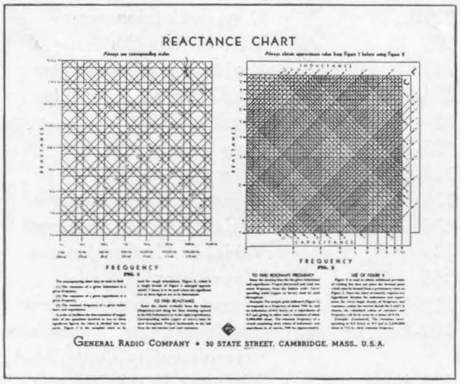
Type	*Description*
154	Voltage Dividers
202-A,-B	Switch
202-Y,-Z	Switch Knob
219-L,-N	Decade Condensers
246	Variable Air Condensers
247	Variable Air Condensers
274-K,-L	Binding Post Assembly
274-ML	Double Plug
293-A	Universal Bridge
329-J	Attenuation Box
333-A	Rheostat Potentiometer
334	Variable Air Condensers
335	Variable Air Condensers
358	Wavemeter
410-A	Rheostat Potentiometers
419-A	Rectifier-Type Wavemeter (replaced by Type 758-A)
433-A	Rheostat-Potentiometer
434-B	Audio Frequency Meter
449-A	Adjustable Attenuator
476-A	Quartz Bar
480-A, B	Relay Racks
493	Thermocouples
505-T, U, R, X	Mica Condensers
509-F, G, K, L	Standard Condensers
516-C	Radio-Frequency Bridge (replaced by Type 916-A and Type 821-A)
516-P2, P3, P4, P5, P6, P7, P10	Accessories
525	Resistors
526	Mounted Rheostat Potentiometers
530-C	Band-Pass Filter
533-A	Rheostat Potentiometer
539-P, X	Variable Air Condenser
544-P2	A-C Power Supply, 90 volts
574	Wavemeter (replaced by Type 566-A)
578-AR, BR, CR, AT, BT, CT	Shielded Transformer
586	Power-Level Indicators
588-AM	Direct-Current Meter
602-E	Decade Resistance Box
611-C	Syncro Clock
613-B	Beat-Frequency Oscillator (replaced by Type 913-A)
613-P1	A-C Power Supply
620-AM	Heterodyne Frequency Meter and Calibrator, Cabinet Model (the relay-rack model, Type 620-AR, is still available)

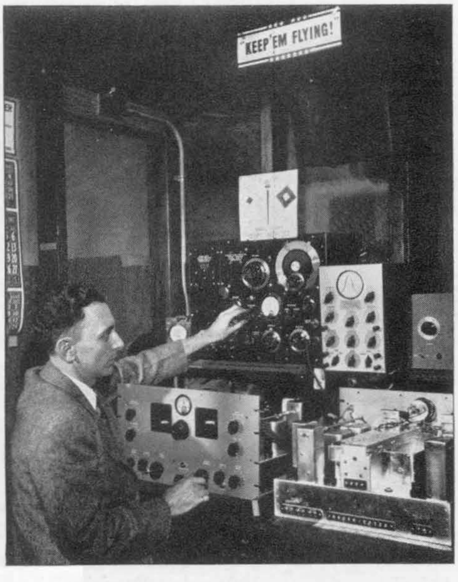
Type	*Description*
625-A	Bridge
625-P1	Condenser
641	Audio Transformers
642-D	Volume Control
646-A	Logarithmic Resistor
653	Volume Controls
664-A	Thermocouple
666-A	Variable Transformer
669-A, R	Compensated Slide Wire Resistor
670-BW, FW	Compensated Decade Resistor
672-A	Power Supply
673-A	Power Supply
677	Coil Forms
678	Coil Bases
682-B	Frequency Deviation Meter
684-A	Modulated Oscillator
686-A	Power Level Indicator
707-A	Cathode-Ray Null Detector
707-P	Accessories
713-BM, BR	Beat-Frequency Oscillator (replaced by Type 913-A)
714-A	Amplifier
716-P2	Guard Circuit
721-A	Coil Comparator
722-FU	Precision Condenser
731-A	Modulation Monitor
732-B	Distortion and Noise Meter
733-A	Oscillator
739-A, B	Logarithmic Condenser
741	Audio Transformers
755-A	Condenser
759-P21	Extension Cable and Tripod
769-A	Square-Wave Generator
774-R1, R2	Patch Cords
813-B	Oscillator, 400 cycles (the 1000-cycle model is still available)
815-C	100-cycle Precision Fork (still available on special order)

Not included in the above are redesigned instruments for which only the type letter was changed, keeping the same type number as, for instance, the replacement of Type 716-A Capacitance Bridge by Type 716-B.

REACTANCE CHART NOW AVAILABLE IN 8½ x 11 SIZE

● **A NUMBER OF "EXPERIMENTER"** readers have recently requested copies of the General Radio reactance chart suitable for laboratory notebook use. We are glad to announce that these are now available with standard 3-hole punching for binding in an 8½ x 11-inch ring binder. A copy will be sent on request. The larger size for wall mounting is also still available.





● **THOUSANDS OF GENERAL RADIO SIGNAL GENERATORS** are working overtime in plants manufacturing military radio equipment. In some plants, we are informed, generators have been operating for months without being turned off.

This photograph, published through the courtesy of FM Magazine, shows Signal Corps inspector E. P. Mayer testing receivers with a Type 605-B Standard-Signal Generator in a final inspection cage at the Hammarlund Manufacturing Company.

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also IN THIS ISSUE

THE EFFECT OF HUMIDITY ON ELECTRICAL MEASUREMENTS

● **IT IS AT THIS TIME** of year that complaints come in regarding the erratic behavior of electrical measuring equipment, particularly precision impedance bridges. The various stories conflict. Sometimes the bridge seems to read high, sometimes low; the balance may drift badly or suddenly jump to a new value; it may show increasing errors as the frequency is lowered, or the balance may shift with applied voltage. At first glance it seems that there must be as many causes as kinds of error. Actually, there is just one cause, high relative humidity. Testing laboratories and research workers in the northern latitudes are experiencing for a few months what their brothers to the South contend with for half the year and what the few in the tropics fight the year around.

High relative humidity affects insulation in two ways. If the insulation is porous, moisture will be absorbed into the volume of the material while, if moisture wets the surface, a thin film of water is formed

The new Rohm and Haas physics laboratory is one of the most complete plastics testing laboratories in the country. This photograph shows two General Radio bridges set up to measure the dielectric properties of discs of Plexiglass.

covering the whole surface. Water distributed throughout the interior of an insulator produces interfacial polarization which causes an increase in capacitance, dissipation factor, and volume conductivity. The amounts of these increases vary with the relative humidity and inversely with the frequency.[1] At 100% relative humidity and a frequency of 60 cycles, increases of as much as 50% in capacitance, of a million-fold in conductivity, and up to a dissipation factor of 1.0, are quite possible for such porous materials as filled and laminated thermosetting plastics, many thermoplastics and natural fibers like cotton, wool, and silk. The rate at which a porous material absorbs water and the tenacity with which it holds it depend greatly on the cross section of the pores. When these approach molecular dimensions, as in silica gel, which is a silicate having microscopic pores produced by suitable heat treatment, the material acts as a desiccant, and the absorbed water can be removed only by heating above the boiling point. Mica and some ceramics act in this manner. Only quartz and most glasses, some steatites, polystyrene, and a few other polymers are free from volume absorption and the accompanying deterioration of dielectric properties.

The formation of a surface film of water on an insulator is determined by the ease with which water wets the surface, which in turn is measured by the contact angle between the surface and a drop of water on the surface.[2] Most of the porous materials that show large volume absorption also wet very easily. A microscopic roughness of the surface helps film formation. Quartz, glass, and steatite also wet easily. Only wax, polystyrene, and some other polymers successfully prevent the formation of a continuous film. The condition of the surface is also important. Dust and particularly acid perspiration from handling greatly aid wetting. The conductivity of even a thin film is enormous. Merely breathing on the surface of a good insulator like quartz will lower the insulation resistance between terminals spaced ¾ inch apart from above 10 MMΩ to below 1 MΩ. A film so formed will vanish rapidly if the surface is chemically clean and the relative humidity low. On a dirty surface, however, the film persists and can be removed only by thorough cleaning or by heating.

Because there are no rigid stable insulators which are unaffected by moisture, it is customary to impregnate them or at least to coat their surfaces with one of the water-repellent substances such as wax, polystyrene, or the newer silicon resins. Any of these materials operates successfully on the non-porous insulators, such as glass and steatite, so long as perfect adhesion is maintained. Large changes in temperature, particularly toward freezing, will produce cracking and chipping of the surface material because of the differences in temperature coefficients of linear expansion, and because most coatings, the waxes in particular, become brittle at the lower temperatures. Any moisture film which then forms between the insulation and the coating persists and can be removed only by complete cleaning of the surface or by heating.

On porous materials a thin protective coating is of no value because even the waxes are themselves somewhat porous.

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[1] R. F. Field, "Frequency Characteristics of Decade Condensers," General Radio *Experimenter*, Vol. XVII, No. 5, Oct., 1942, pp. 1-7.

[2] On the well waxed surface of an automobile during a rain, large drops stand with a small re-entrant angle, the area of contact being smaller than the maximum section of the drop.

Such a coating decreases the rate at which moisture penetrates to the inner material, but continued exposure to high relative humidity will eventually result in the same equilibrium conditions. For reasonable success, wax coatings must be heavy, the result of multiple dippings, and of the order of 0.1 inch.

In all General Radio instruments great care has been taken to provide adequate protection against high relative humidity. All solid dielectric condensers are hermetically sealed or heavily waxed. All high-valued resistors are waxed or similarly protected. All steatite insulation is protected by a surface coating by the manufacturer. Mica-filled phenolic or polystyrene is used as insulation for mounting all high impedances. All wires for cables are rubber covered with an identifying braid wax - impregnated. These precautions are sufficient to allow normal operation under 90% relative humidity at 90° F. of all instruments except the 0.1% impedance bridges. An even more severe test occurs when, at 90% relative humidity, the temperature fluctuates sufficiently to reach the dew point and cause direct moisture condensation. Under these conditions the operation of an instrument may not meet catalog specifications. If power is dissipated inside the instrument, the heat generated will quickly evaporate the conducting moisture films. Otherwise some time must elapse to allow natural evaporation. A 40-watt lamp or other resistive load maintained inside the case will usually prevent condensation. It will have, however, little effect on moisture absorption.

The Type 716-B Capacitance Bridge is probably as greatly affected by moisture as any of our instruments. All steatite insulated terminals are wax coated, the input transformer is wax sealed, and the bridge wiring is open bus. Only the Type 722 Precision Condenser, used on the capacitance standard, is affected by moisture, and that only in its dielectric losses, not in its capacitance. Its own dissipation factor is defined by its figure of merit $F = DC = 0.04\ \mu\mu f$, corresponding to a dissipation factor of the steatite stator support of 0.004. At about 60% relative humidity, moisture absorption through the wax coating on these bars causes their dissipation factor to rise. A tenfold increase at 90% relative humidity must be expected. This will produce a negative error in the direct reading of dissipation factor exactly equal to the increase in dissipation factor of the precision condenser. No error will appear in parallel substitution measurements.

Another dielectric loss occurs in aluminum-plate air condensers under high humidity conditions from the absorption of moisture by the aluminum oxide on the surface of all the plates. In its dry state aluminum oxide has a small dissipation factor and imparts to the whole condenser a dissipation factor of only 0.0000001, since its contribution is proportional to the ratio of the thickness of the oxide film, about 10 millionths of an inch, to the plate spacing of 30 mils. When exposed to moisture the dissipation factor of the oxide is an exponential function of the relative humidity,[3] increasing a decade of dissipation factor for every 15% rise in relative humidity. At 90% the air condenser has a dissipation factor of about 0.01. Since the dielectric loss occurs on the surfaces of all the plates, the air condenser behaves like a variable solid dielectric condenser, and

---

[3] A. V. Astin, "Nature of Energy Losses in Air Capacitors at Low Frequencies," *Journal of Research of the National Bureau of Standards*, Vol. 22, No. 6, June, 1939, pp. 673-695.

its dissipation factor does not cancel out even in parallel substitution measurements. As before, the error in the bridge reading is negative.

Both of these kinds of moisture absorption in steatite and in aluminum oxide are troublesome when the relative humidity stays at 60% throughout the day, since at this level only a half day is required to attain equilibrium. A relative humidity of 40% causes no appreciable error, and even a rise to 60% followed by a drop back to 40% within six hours will cause little trouble. The time needed to attain equilibrium increases with the relative humidity and is at least three days at 90%.

Every laboratory should be equipped with some type of hygrometer in order that the possibility of errors in bridge measurements may be anticipated. The ordinary hair hygrometer is very useful in spite of its large errors because it is of the indicating type. A wet and dry bulb hygrometer should be available as a check under extreme conditions. Regular readings of relative humidity during the summer months are fully as important as are those of temperature, for the units being measured are in many cases more liable to be affected by high humidity than the measuring equipment itself. This fact indicates that the bridge readings of dissipation factor may appear to be high or low dependent upon the relative rates at which the unknown condenser and the standard condenser in the bridge change their dissipation factors with humidity. Without a hygrometer this situation cannot be definitely recognized except as the reading of dissipation factor becomes ridiculously low or actually negative. A certain instability of bridge balance will appear at relative humidities above perhaps 70%, as indicated by a more or less steady drift of both capacitance and dissipation factor balance points.

There is little that can be done with existing measuring instruments to eliminate this type of error, short of air conditioning. This should preferably apply to the entire room containing measuring equipment. Then the unknown unit is measured under standard conditions. It is also possible to dry out the measuring instrument by placing a desiccant, such as silica gel, inside its case. However, the amount of moisture which can seep through the joints between panel and case and around the control shaft is amazing. Unless unusual care is taken, it will be necessary to renew the desiccant each working day whenever the relative humidity is above 70%.

— ROBERT F. FIELD

ERRATA IN THE TYPE 716-B INSTRUCTION BOOK

Two errors in the Operating Instructions for TYPE 716-B Capacitance Bridge have recently been discovered.

In Equation 9, page 5, the expression for C_{XP} should be

$$C_{XP} = \Delta C \frac{1 - (\Delta D)^2 \dfrac{C}{\Delta C}}{1 + (\Delta D)^2}$$

and in Equation 10, page 6, the expression for C_{XP} should read

$$C_{XP} = \Delta C \frac{1 + D\left(D' - \Delta D \dfrac{C}{\Delta C}\right)}{1 + D^2}.$$

The latter correction has been made in books currently being shipped.

CHECKING THE ACCURACY OF AIRCRAFT TACHOMETERS

● **THE CURRENT PROBLEM** in checking aircraft engine tachometers is one of handling the increased number of tachometers and of making sure that the individual tachometer takes advantage of the full tolerance allowed by the acceptance specification.

If the tachometer tolerance is ±25 rpm and if the checking standard has an error of ±10 rpm, the tachometers must each read within ±15 rpm to be accepted. If the checking standard accuracy can be improved to ±2 rpm, the tachometers need only read within ±23 rpm to be accepted. With the increased accuracy more tachometers are accepted at no increase in testing time. The extra time required for handling rejections is eliminated.

The General Radio Type 631-B Strobotac bears the approval of the Civil Aeronautics Administration for the checking of aircraft tachometers. This certificate is earned by the rated accuracy of the Strobotac, which measures speeds between 900 and 14,400 rpm with an error of less than ±1% of the measured value. This statement assumes that the supply from which the Strobotac is operated is a power line tied in with one of the main frequency-regulated power systems of the country. The instantaneous error in the frequency of a regulated 60-cycle power line seldom exceeds ±0.2%, and is usually much less than this figure. A telephone call to the local power company's Dispatcher's Office will give a check on the frequency accuracy to be expected of the local power system.

Engine tachometers are driven from the engine cam shaft which turns at one-half the crankshaft speed. In the instrument laboratory, therefore, the tachometer is checked by comparing its reading with twice the measured speed of the test-stand drive shaft.

There are usually three steps in the tachometer-testing procedure.

(a) The Strobotac calibration is adjusted against the line-controlled synchronous vibrating reed mounted within the instrument reflector, and the Strobotac scale is then set to one-half the desired tachometer test speed.

(b) The speed of the test-stand drive motor is adjusted until the drive shaft appears to stand still.

(c) The scale reading of the tachometer is recorded.

Steps (a) and (b) may be combined, and the possible calibration errors of Step (a) may be eliminated by using a stroboscopic disc and by flashing the Strobotac at the power-line frequency under LINE control. This method permits reduction of possible errors from the ±1% rated Strobotac maximum error to the power-line frequency error of usually less than ±0.2%.

The stroboscopic disc of Figure 1 may

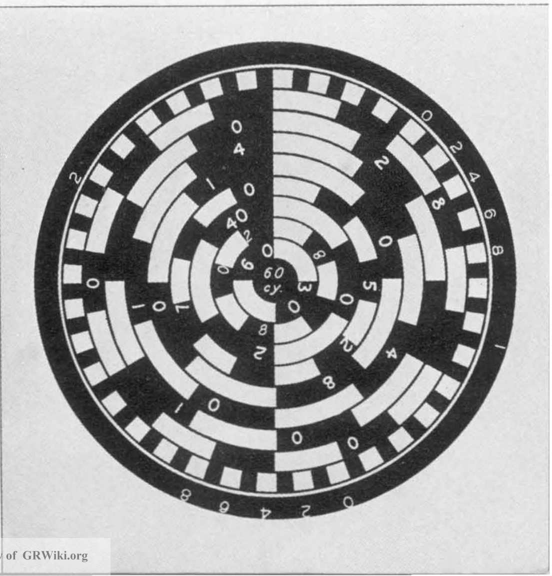

Figure 1. Tachometer test disc for Strobotac. Copies are available on request.

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The General Radio TYPE 631-B Strobotac bears the approval of the Civil Aeronautics Administration for the checking of aircraft tachometers. This certificate is earned by the rated accuracy of the Strobotac, which measures speeds between 900 and 14,400 rpm with an error of less than ±1% of the measured value. This statement assumes that the supply from which the Strobotac is operated is a power line tied in with one of the main frequency-regulated power systems of the country. The instantaneous error in the frequency of a regulated 60-cycle power line seldom exceeds ±0.2%, and is usually much less than this figure. A telephone call to the local power company's Dispatcher's Office will give a check on the frequency accuracy to be expected of the local power system.

Engine tachometers are driven from the engine cam shaft which turns at one-half the crankshaft speed. In the instrument laboratory, therefore, the tachometer is checked by comparing its reading with twice the measured speed of the test-stand drive shaft.

There are usually three steps in the tachometer-testing procedure.

(a) The Strobotac calibration is adjusted against the line-controlled synchronous vibrating reed mounted within the instrument reflector, and the Strobotac scale is then set to one-half the desired tachometer test speed.

(b) The speed of the test-stand drive motor is adjusted until the drive shaft appears to stand still.

(c) The scale reading of the tachometer is recorded.

Steps (a) and (b) may be combined, and the possible calibration errors of Step (a) may be eliminated by using a stroboscopic disc and by flashing the Strobotac at the power-line frequency under LINE control. This method permits reduction of possible errors from the ±1% rated Strobotac maximum error to the power-line frequency error of usually less than ±0.2%.

The stroboscopic disc of Figure 1 may

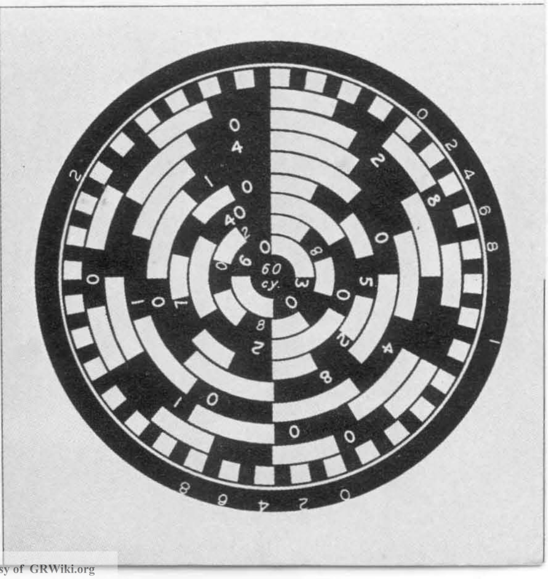


FIGURE 1. Tachometer test disc for Strobotac. Copies are available on request.

TORSIONAL VIBRATION ANALYSIS WITH THE TYPE 736-A WAVE ANALYZER

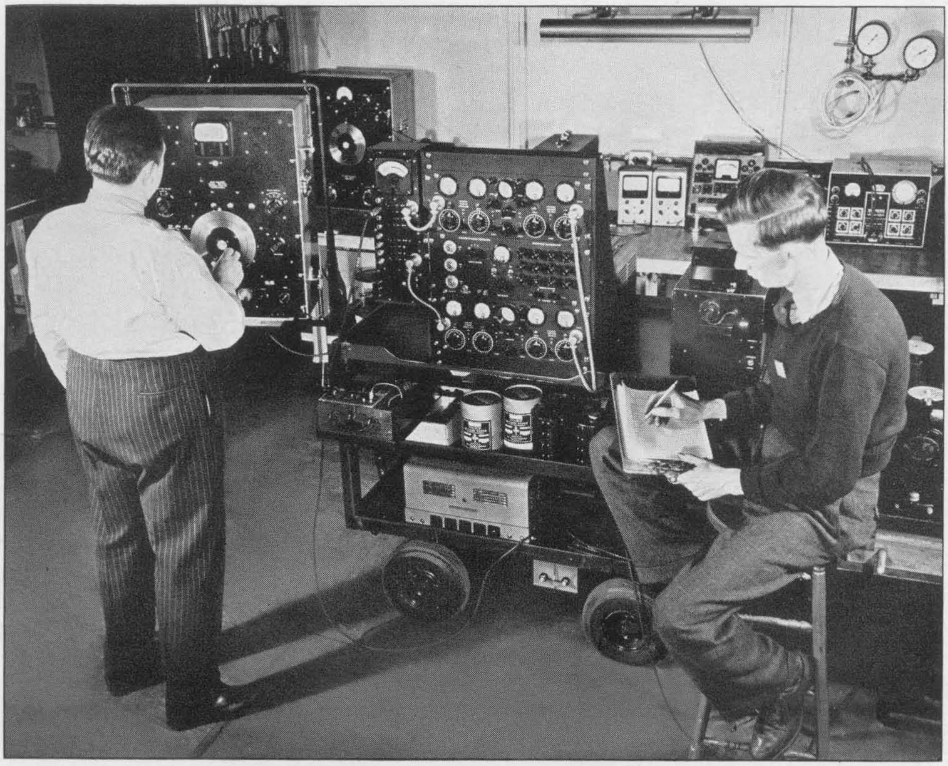
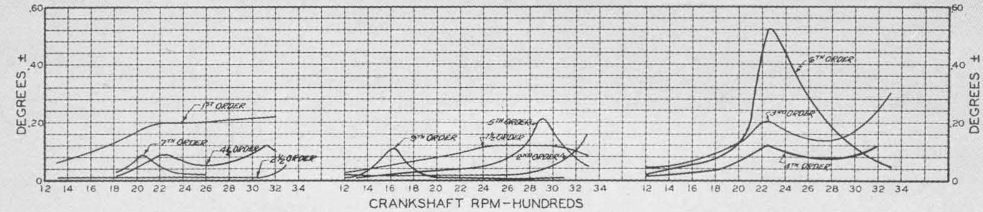


FIGURE 1. Test setup for measuring torsional vibration at the Lycoming laboratories.

● **ALTHOUGH** the TYPE 760-A Sound Analyzer and the TYPE 762-A Vibration Analyzer are recommended for general purpose sound and vibration analysis, there are specific applications where the use of the TYPE 736-A Wave Analyzer leads to certain operating conveniences and somewhat better accuracy. In Figure 1 is shown a test setup in the laboratories of the Lycoming Division, the Aviation Corporation, using the wave analyzer for the analysis of torsional vibrations in aircraft power plants.

At the lowest frequencies, the resolving power of the wave analyzer is not adequate for satisfactory separation of

FIGURE 2. Plots showing the amplitudes of various orders of vibration as measured with the wave analyzer.



closely spaced non-harmonic components, but for vibration frequencies directly related to the fundamental engine speed, the selectivity is adequate. For instance, at a fundamental (first-order) vibration of 20 cycles (per second), the ½ order and 1½ order components fall at 10 and 30 cycles, respectively. The discrimination of approximately 30 db between such components is adequate for most torsional vibration analysis.

At extremely high frequencies the Type 736-A suffers somewhat in comparison to the Type 760-A, because the relatively sharper response curve makes tuning difficult when the frequencies under observation are not stable. For the range of frequencies normally encountered (fundamental speeds in the range 1000-3000 rpm) in torsional studies on aircraft engines, however, the selectivity characteristics of the wave analyzer are satisfactory.

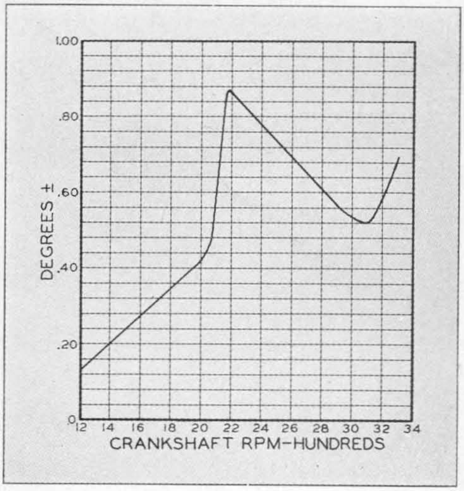


Figure 3. Maximum amplitudes of the resultant recorded vibration wave measured from oscillograms.

A series of plots typical of the amplitude of various orders of vibration, as the driving speed is varied over a wide range, is shown.

— Ivan G. Easton

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

IN THIS ISSUE

IDENTIFICATION OF HARMONICS IN A HARMONIC SERIES

● **IN USING** frequency standards, the useful output of which consists of one or more series of harmonics, the ready identification of certain or all of the harmonics in a given frequency range is one of the first problems encountered in calibrating equipment against the standard. Basically the problem is always the same: (1) The identification of a key point, or of widely separated key points; (2) dividing the interval between such points, or the frequency range about one such point, into smaller frequency intervals, and (3) subdividing such intervals into successively smaller intervals. Depending on the method used, the identification and subdividing steps may or may not be combined into a single operation.

I. Using Calibrated Oscillator or Receiver

Within certain ranges, the simplest method depends on the calibration of an oscillator or a receiver, or both. These calibrations must be sufficiently accurate and stable so that the errors are substantially less than one half of the fundamental frequency of the harmonic series, that is, substantially less than one half of the frequency interval between successive harmonics.

If a fine calibration of a piece of equipment is required, it is obvious that as harmonic series having lower and lower fundamental frequencies (to obtain calibrating points nearer and nearer together) are used, a point will be reached where any given oscillator or receiver calibration is not sufficiently precise to identify positively the frequency of any given harmonic.

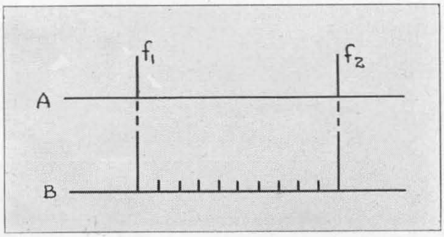


FIGURE 1. 100-kc harmonics identified by calibration of oscillating receiver are shown at A. Knowing f_1 and f_2, points at 10-kc intervals are filled in as at B and the frequencies are known.

II. Using Calibrated Oscillator or Receiver and Successive Harmonic Series

By use of different harmonic series, *in turn*, however, this situation can be overcome. For example, suppose the receiver calibration in the frequency range of interest to be good to ± 5 kc. It is obvious that this calibration would not serve to identify 10-kc harmonics, but it would be entirely adequate to identify 50-kc or 100-kc harmonics.

By first spotting the identifiable 50-kc or 100-kc points on the scale of the equipment being calibrated, such "key" points serve for positive checking when calibration points at, say, 10 kc, or smaller intervals, are filled in as shown in Figure 1.

III. Identifying Harmonics Separated by a Desired Interval

When the frequency range or span of an oscillator is to be checked as covering certain limits, it is convenient to be able to identify two harmonics of a series which are not adjacent harmonics. This span should be checked before detailed calibration is started.

If an auxiliary oscillator is set at a fundamental frequency equal to the de-

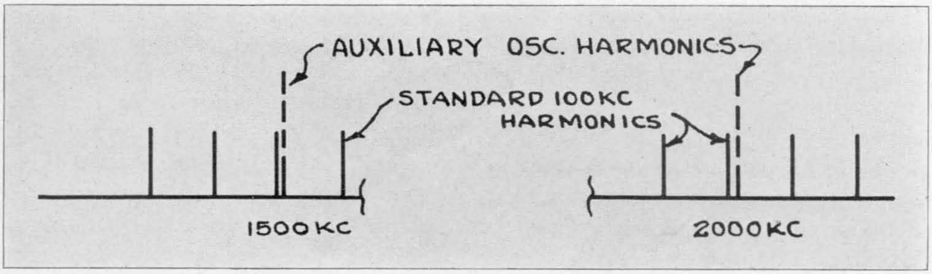


FIGURE 3. Showing how two standard harmonics marking a particular frequency span are identified using an auxiliary oscillator.

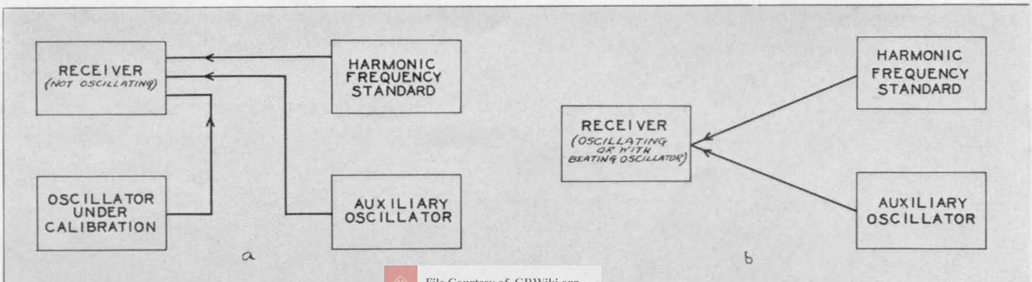
sired span, one of its harmonics then falls at the bottom and one at the top of the desired range. If the span is not a multiple of the fundamental of the harmonic series of the standard, a test span can be chosen which is such a multiple.

If this is done, the auxiliary oscillator is preferably not set in exact zero beat with the standard. If the oscillator is offset slightly, then the top and bottom points of the test span will be identified by two harmonic frequencies of the standard marked by a characteristic double beat tone when picked up in a non-oscillating receiver, while all other standard frequency harmonic points will be marked by single beat tones, as the oscillator frequency is varied through its range. A block diagram of the system is shown in Figure 2a. An oscillating receiver, or one with a heterodyning oscillator, can also be calibrated by this method, as shown in Figure 2b.

As an example, let us assume that one range of a multi-range frequency meter to be calibrated covers a span from 1460 to 2090 kc. If the auxiliary oscillator is set at 500 kc, a test span of 1500 to 2000 kc is marked off by the third and fourth harmonics. If this oscillator is set off from 500 kc by 30 cycles or so, then a characteristic double beat will be heard when the test oscillator is set at 1500 or 2000 kc. When these two points have been checked as falling within normal limits on the frequency meter scale, the auxiliary oscillator is turned off and final calibration started in terms of the standard alone.

This same procedure provides for setting up, in effect, a harmonic series of higher fundamental frequency than the highest available from a given frequency standard. For example, if the highest frequency harmonic series is 50 kc, an auxiliary oscillator set at 500 kc, and slightly offset from the standard, identifies every 10th 50-kc harmonic by the characteristic double beat tone, which is equivalent to a standard harmonic series of 500 kc. This series extends over the range covered by harmonics of the auxiliary oscillator. Final calibrations at any such points should

FIGURE 2. (a) Block diagram showing the process of calibrating an oscillator by means of an auxiliary oscillator set to the desired frequency span. (b) A similar system for calibrating a receiver.



be taken directly against the 50-kc harmonics, with the auxiliary oscillator effectively disconnected from the detector.

Finally, if several series of standard frequency harmonics are available, identification of any desired harmonic of the low frequency series can be made by counting, provided only that harmonics of the highest frequency series can be identified. For example, if a receiver calibration identifies any harmonic of a 100-kc series, and is set to one such harmonic, we can, on substituting a 10-kc series, count the number of 10-kc points passed over in tuning the receiver to either lower or higher frequencies. By counting not more than five 10-kc harmonics, we can set the receiver to any required 10-kc multiple.

For example, if 1670 kc is to be identified, set the receiver at 1700 kc, as checked against 100-kc harmonics. Leaving the receiver at this setting, substitute the 10-kc harmonic series. Tuning the receiver toward lower frequencies, the first 10-kc harmonic reached is 1690 kc, the second 1680, and the third is the desired point of 1670 kc.

IV. Identifying Harmonics on Uncalibrated Equipment

It is feasible, and, in many cases, very convenient to have a system of identifying *any standard frequency harmonic*, without the necessity of having any calibrated radio-frequency equipment. To do this it is necessary to have means of measuring audio frequencies with precision but, since such equipment is usually available with the frequency standard, this is generally no new problem.

If it is desired, for example, to know which 100-kc standard harmonic has been tuned in on an *uncalibrated* receiver, an auxiliary setup or "identifier," consisting of a crystal oscillator and 100-kc multivibrator, is needed. This crystal oscillator need not be of elaborate design. If the crystal has a low temperature coefficient and the circuit is provided with a *fine* frequency adjustment, for purposes of accurately adjusting the difference in frequency, or "offset," between the standard and identifier frequencies, occasional readjustment is all that is required.

The use of an "offset" frequency standard as a means of avoiding very low beat frequency differences when measuring radio frequencies is well known. The particular feature of using a specific offset for identification purposes was proposed by the writer's co-worker, Mr. H. H. Hollis.

This auxiliary crystal oscillator is adjusted to a frequency that is a definite number of cycles below 100 kc and the multivibrator is controlled from it. For example, if the crystal is set Δ cycles low on the 100-kc fundamental, the frequency of any identifier harmonic is $nf_i = n(f_s - \Delta) = nf_s - n\Delta$ cycles, where f_i is the identifier fundamental frequency and f_s is the standard frequency.

Now, if the *uncalibrated* non-oscillating receiver is tuned to some harmonic

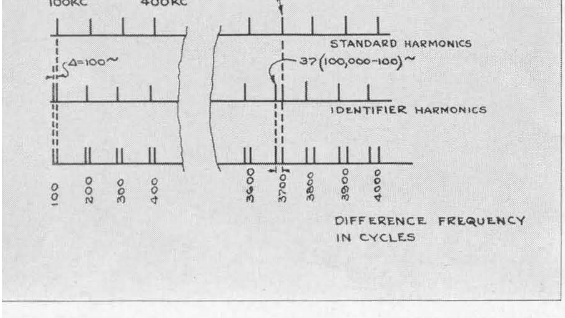


FIGURE 4. Showing operation of identifier.

of the standard, its frequency is nf_s. If, then, the standard and identifier outputs are both connected to the receiver input, a beat output from the receiver is obtained equal to

$$\begin{aligned} f_b &= nf_s - (nf_s - n\Delta) \\ &= nf_s - nf_s + n\Delta \\ &= n\Delta \text{ cycles} \end{aligned}$$

which is the beat frequency measured with the audio-frequency measuring equipment.

In general, we are not interested in the *number* of the harmonic n; we wish to know its *frequency*. By choosing Δ appropriately, the beat $n\Delta$, *in cycles*, can be made equal numerically to the frequency nf_s of the standard harmonic, *in kilocycles*.

For example, take Δ as 100 cycles, as shown in Figure 4. If the receiver is tuned to the 37th harmonic of the 100-kc standard, the beat output of the receiver will be 100 x 37 = 3700 cycles. The frequency of the harmonic to which the *uncalibrated* receiver is tuned is 3700 kc. The next higher harmonic (38th) would give a beat output of 3800 cycles.

From this we can see that the frequency of the identifier crystal oscillator should be set carefully just 100 cycles below the standard, which is most easily done by tuning in a known high-frequency harmonic and adjusting the crystal oscillator to obtain the correct beat frequency. We also can see that, for a given Δ and a given audio-frequency measuring range, there is an upper limit to the number of standard harmonics which can be identified. For example, if the audio-frequency measuring equipment covers a range up to 5000 cycles, the highest standard frequency harmonic which can be identified is 5000 kc or 5 Mc.

With some care in adjusting the identifier crystal oscillator frequency, and in operating the audio-frequency measuring equipment, a Δ of 10 cycles can be used, which gives beat frequencies one tenth of those given above. The frequency of the harmonic in kc is then *10 times* the audio-beat frequency. The upper frequency limit is also ten times higher — 50,000 kc or 50 Mc.

From the preceding descriptions we can see that, to obtain decimal multipliers for converting the observed beat frequency to the frequency of the standard harmonic, we should choose a Δ which is a decimal fraction of the standard frequency. For example, if the standard frequency is 50 kc, a Δ of 50 cycles gives beat frequencies in cycles which are numerically equal to the frequencies of the standard harmonics in kilocycles.

If the identifier is set up as described above for identification of standard harmonics on the direct-reading basis, then the addition of a lower frequency multivibrator to the identifier will provide for identifying the harmonics of this lower standard frequency. If a 10-kc multivibrator be added to the identifier of the preceding paragraph, the effective Δ is 50 divided by 5, becoming 10 cycles. Therefore the audio beat obtained between a standard 10-kc harmonic series and the 10-kc series from the identifier is again, in cycles, equal to the frequency of the 10-kc harmonic, in kilocycles.

A further limitation on the number of harmonics which can be identified by this method comes about when the beat frequency $n\Delta$ reaches or exceeds one half the fundamental frequency of the harmonic series. With Δ taken as 10 cycles, as described in the last paragraph, with a 10-kc harmonic series, $n\Delta$ becomes equal to $f_s/2$ when the beat is 5000 cycles, corresponding to the 500th harmonic. While it is possible to

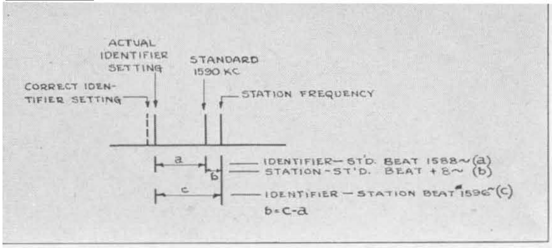


FIGURE 5. Showing use of identifier in avoiding very low beat frequencies in measuring a radio frequency very near a standard harmonic.

interpret the results when the beat frequency effectively exceeds this value, it is generally simpler and much more convenient to choose a value for Δ which avoids this situation in the frequency range of interest.

Summarizing, a value for Δ can be chosen which will identify practically all useful harmonics of a high frequency series, within the limits of a given audio-frequency measuring range. This same value of Δ will identify harmonics of a lower frequency series up to the limit of the audio-frequency measuring range or $f_s/2$, whichever occurs at the lower frequency, where f_s is the fundamental of the low frequency harmonic series.

In many cases this method of identification need be applied only to the highest frequency harmonic series of the frequency standard. In any given frequency range a large number of identified key frequencies are then available. The intervals between these known key frequencies can then be subdivided by one of the other methods described, without the necessity of using a lower frequency identifier series.

The use of a definite value of offset from standard for the identifier crystal oscillator frequency in no way impairs the use of the system in avoiding low beat frequencies when measuring a radio frequency. If a broadcast station frequency is being measured, the beat obtained between a 10-kc standard harmonic and the station frequency would only be a few cycles. If the audio beat between the standard and identifier series, at the harmonic corresponding to the station frequency, is first measured and then the beat between the identifier series and the station frequency, the difference of these beat frequencies is the number of cycles that the station is off frequency.

For example, suppose a station at 1590 kc is being checked, as illustrated in Figure 5. If the identifier is set exactly, the beat difference between the identifier and standard at this harmonic would be 1590 cycles. Suppose the identifier is slightly off frequency, giving a beat of 1588 cycles. If the beat between the identifier and station frequencies is 1596 cycles, the station is 1596 − 1588 = +8 cycles (high); if the beat were 1583 cycles, the station would be 1583 − 1588 = −5 cycles, or the station would be 5 cycles low. The error in setting the identifier does not appear in the final result. —J. K. CLAPP

SERVICE DEPARTMENT NOTES

Tell Us What Is Wrong

In writing about erratic operation of an instrument, please describe in detail the type of service, hours of usage, operating conditions, power source, and results obtained from following directions given in Instruction Books, and Service and Maintenance Notes. It will often be possible for us to analyze the trouble and to send directions for its correction by return mail.

If it is necessary that an instrument be returned for reconditioning, this detailed information will prevent delay in doing the work.

Service and Maintenance Notes

This information is mailed without charge to all users of General Radio equipment. The Notes will help you in making adjustments and repairs, thus avoiding time lost in having reconditioning done at the factory. If you do not have a set of Service and Maintenance Notes, send us a list of your General Radio instruments, giving type and serial numbers, and your copy will be mailed promptly.

Check Your Equipment Now

Constant usage of General Radio equipment will eventually result in the wearing of moving components, deterioration of tubes and batteries, changes in the values of resistors and capacitors, and the collecting of dust and grit throughout the assembly. These conditions occur very gradually and the effects are not noticed until errors become serious or poor operation develops.

Why not check your equipment now to see if it conforms to the specifications in the catalog? The information given in the Instruction Book and in the Service and Maintenance Notes will help you in determining if operation is normal and in making readjustments. Keep your instruments in first-class operating condition in order to get accurate results from your measurements.

VARIACS

Most of the Variacs returned for repairs have damaged windings. Defective brushes or poor contact of the brushes on a corroded or blackened winding surface result in arcing, eventually damaging the coils. Occasional inspection and cleaning of your Variacs will prevent delays caused by return to the factory for repairs. Orders for replacement brushes are shipped promptly. Please specify type of Variac on your order.

Replacement Parts

While an effort is made to maintain a reasonable stock of parts, such a supply must necessarily be limited, because of general shortages. In placing a requisition for replacement parts, please order only the amount sufficient for your immediate needs. Orders for larger quantities may deprive another customer from getting parts needed in an emergency.

Whenever possible, repair minor damage in your own plant. If you cannot make repairs to parts of General Radio manufacture, why not return them to us for repair rather than order a replacement? Prompt service can be given and strategic materials will be conserved.

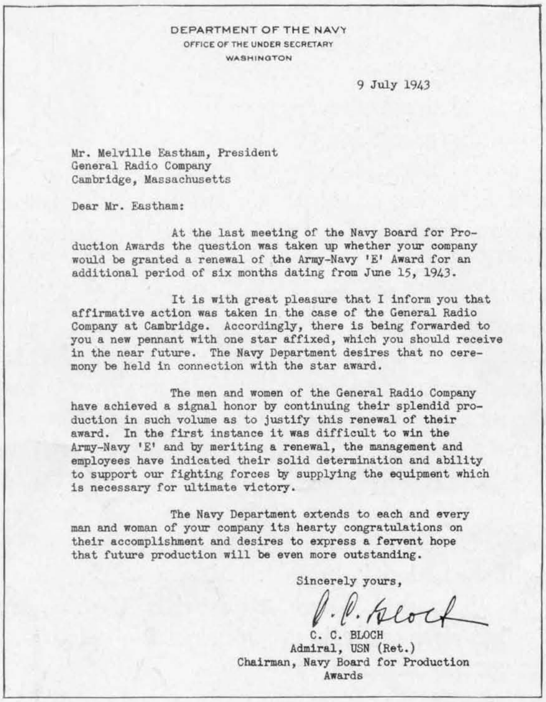
— H. H. Dawes

Group of employees holding the "E" banner.

A STAR FOR OUR "E" BANNER

The men and women of the General Radio Company are proud that their efforts have merited a renewal of the Army-Navy "E" award. To our suppliers and our subcontractors we express our thanks for their help in adding this star to our "E" banner.

The Navy's letter of award.



DEPARTMENT OF THE NAVY
OFFICE OF THE UNDER SECRETARY
WASHINGTON

9 July 1943

Mr. Melville Eastham, President
General Radio Company
Cambridge, Massachusetts

Dear Mr. Eastham:

At the last meeting of the Navy Board for Production Awards the question was taken up whether your company would be granted a renewal of the Army-Navy 'E' Award for an additional period of six months dating from June 15, 1943.

It is with great pleasure that I inform you that affirmative action was taken in the case of the General Radio Company at Cambridge. Accordingly, there is being forwarded to you a new pennant with one star affixed, which you should receive in the near future. The Navy Department desires that no ceremony be held in connection with the star award.

The men and women of the General Radio Company have achieved a signal honor by continuing their splendid production in such volume as to justify this renewal of their award. In the first instance it was difficult to win the Army-Navy 'E' and by meriting a renewal, the management and employees have indicated their solid determination and ability to support our fighting forces by supplying the equipment which is necessary for ultimate victory.

The Navy Department extends to each and every man and woman of your company its hearty congratulations on their accomplishment and desires to express a fervent hope that future production will be even more outstanding.

Sincerely yours,

C. C. Bloch
C. C. BLOCH
Admiral, USN (Ret.)
Chairman, Navy Board for Production
Awards

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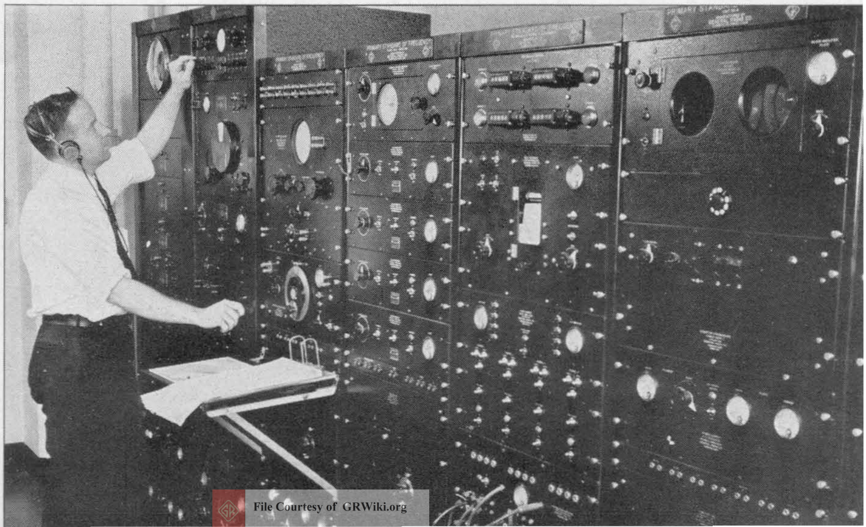
ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

CALIBRATION OF EQUIPMENT IN THE LOW AND MEDIUM RADIO-FREQUENCY RANGES, IN SMALL STEPS OF FREQUENCY

● **THE PROBLEM** of calibrating an oscillator or receiver, at well separated points, in terms of harmonics from a frequency standard is well understood, and is easily solved. Referring to Figure 2a, if the harmonics from the standard are multiples of 10 kc, or of a higher frequency, a calibrated receiver serves to identify the individual harmonic frequencies without ambiguity. The combined selectivity of the tuning of the receiver, the limited pass band of the audio frequency part of the receiver, the telephones, and the operator's ear serve to suppress very largely the "extraneous" beats. If the receiver can be made to oscillate, or if any noise or hum is present, then the oscillator can be set, with high precision,

FIGURE 1. Measuring frequencies in the General Radio laboratories.



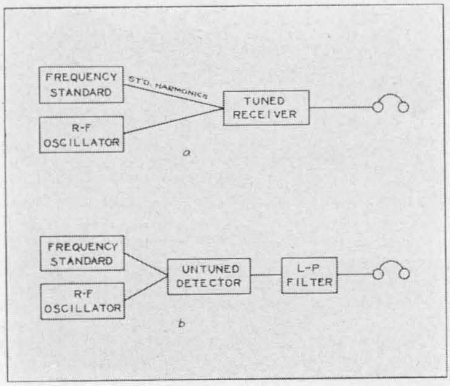


FIGURE 2. Block diagrams showing the method of calibrating an oscillator in terms of a harmonic frequency standard; (*a*) with tuned receiver, (*b*) with an untuned detector.

to zero beat with the standard harmonic frequencies by adjusting it so that the "flutter" heard on the audio beat tone, or background noise, is brought to a very low frequency.

If now it is necessary to calibrate the oscillator in smaller steps of frequency than 10 kc, and harmonics of a lower fundamental frequency, such as 1 kc, are used, a very confusing series of beat tones is heard in the telephones. This is brought about because the principal receiver output no longer consists of the beat between the oscillator and a *single* standard frequency harmonic. When using a 1-kc harmonic series, and with the oscillator set near zero beat against one harmonic, beats between the oscillator and standard are passed by the receiver for several harmonics both above and below the one to which the oscillator is adjusted.

This situation is illustrated in Figure 3. As the oscillator frequency is increased, beats are heard in the receiver output which increase in frequency for standard harmonics below the oscillator frequency; beats are also heard which decrease in frequency for standard harmonics above the oscillator frequency. The upper extent of the diagram is limited by the over-all receiver pass band, as mentioned above.

For a particular oscillator setting, such as represented by f_0, Figure 3, the receiver output contains the various beat frequencies 1, 2, 3 . . . up to the limit passed by the receiver. These are seen to be the desired beat frequency represented by 1 and other beats which consist of multiples of the standard frequency (1 kc) plus or minus the desired beat frequency, represented by 2-3, 4-5, etc.

If the receiver output is deliberately given a sharp cut-off at a frequency slightly greater than one half the standard frequency, represented by the line X-Y, Figure 3, then the confusing beats are entirely eliminated except for a very small region halfway between standard frequency harmonics. In this small region both beats are very nearly one half the standard frequency. If the oscillator is set very nearly halfway between two standard harmonics, the receiver output consists of two frequencies, one very slightly more than one half the standard frequency and one very slightly less. These two frequencies combine to give the effect of a single frequency waxing

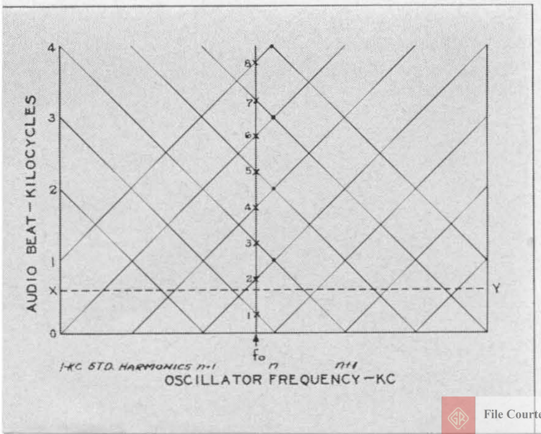


FIGURE 3. Illustrating the formation of beat frequencies as the oscillator frequency is varied.

and waning in intensity at a rate equal to the difference in frequency. If the oscillator is set so that the waxing and waning takes place very slowly, or the "flutter" is brought to a very low frequency, then the oscillator is adjusted with considerable precision to a frequency just halfway between two standard harmonic frequencies.

For many purposes it is desirable to avoid the need of tuning a receiver to successive standard frequency harmonics, when an oscillator is being calibrated. An untuned detector can be used, as shown in Figure 2b, if separate means are used for identifying key points on the oscillator calibration. To avoid confusing beats, a low-pass filter, with a cut-off frequency slightly over one half the standard frequency, should be used.

Because no radio frequency selectivity is provided, a new series of extraneous beat frequencies will be heard in the detector output, if the oscillator output contains harmonics. These beats are formed as follows: while fundamental frequency of the oscillator being calibrated is changed from one standard frequency harmonic, n, to the next higher, $n + 1$, the second harmonic of the oscillator is changed from twice the first standard frequency, $2n$, to twice the second, $2(n + 1)$ or $2n + 2$. In other words, the second harmonic of the oscillator has moved over two harmonic intervals. If the oscillator is set halfway between the two harmonics n and $n + 1$, the frequency is $n + \frac{1}{2}$. The frequency of the second harmonic is twice this, $2\ (n + \frac{1}{2})$ or $2n + 1$, which is a standard harmonic point.

As judged by the fundamental frequency of the oscillator, this simply means that if the oscillator is set halfway between two standard harmonics a zero beat is heard, due to the second harmonic. The second harmonic divides the fundamental interval in half. Similarly, the third harmonic divides the interval into three parts; the fourth harmonic divides it into four parts, and so on.

It is important to realize that this pattern of subdivision of the interval between two successive standard harmonics is always the same regardless of the numbers of the harmonics and regardless of the value of the standard fundamental frequency. The pattern is illus-

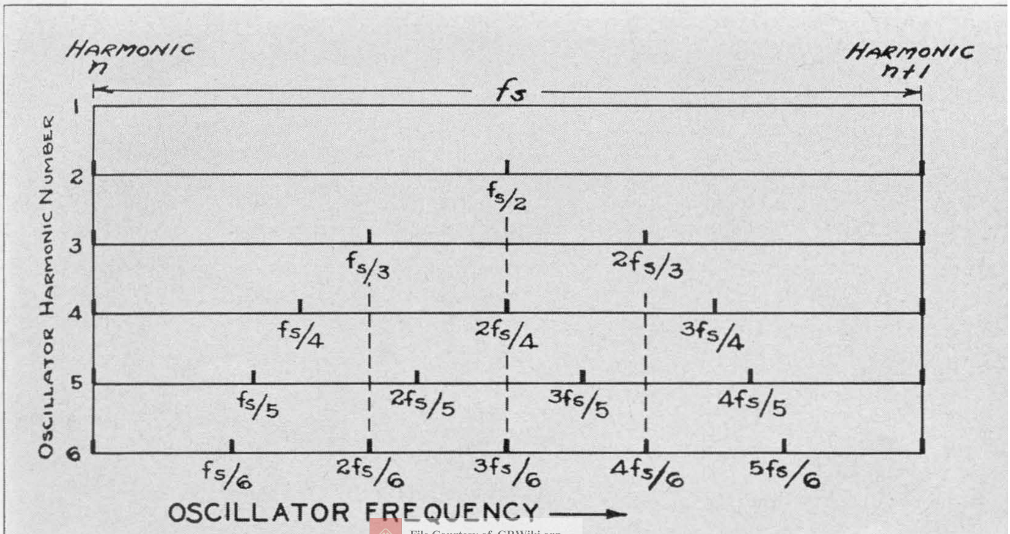


FIGURE 4. Pattern of harmonic beats which subdivide the standard-frequency interval.

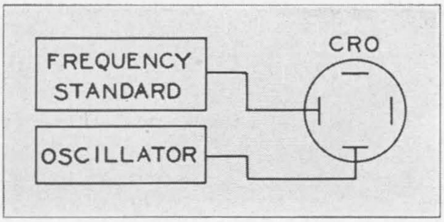


FIGURE 5. Block diagram showing how standard and unknown frequencies are connected to a cathode-ray oscillograph for obtaining Lissajous figures.

trated in Figure 4 which gives the values of all of the frequencies corresponding to zero beat points in one harmonic interval, for harmonics up to the sixth. These points are easily identified and in some cases are a very useful means of subdividing a given standard frequency interval into smaller parts.

A cathode-ray oscillograph is a very useful and versatile device for use in making frequency comparisons and measurements. The simplest application is illustrated in Figure 5, where a standard frequency is applied to the horizontal deflection plates and an oscillator to be calibrated is connected to the vertical deflection plates. The familiar Lissajous patterns will only be briefly described here.* In Figure 6 is shown the type of pattern obtained when the oscillator frequency is three times the standard frequency. When the pattern stands still, the oscillator is exactly three times the standard frequency; the form of the pattern depends on the phase difference of the standard and oscillator voltages.

If the oscillator frequency differs very slightly from the standard, the pattern changes progressively through the forms shown and back again. The ratio between oscillator and standard frequencies is found, for any pattern, by counting the tangent points along a horizontal side, such as d, e, f, and dividing by the number of tangent points along a vertical side, such as "a."

Theoretically fractional ratios, involving other than small integers, such as 27/19, could be identified, but with complicated figures checking is very time-consuming. Also, the principal interest is generally attached to integral ratios.

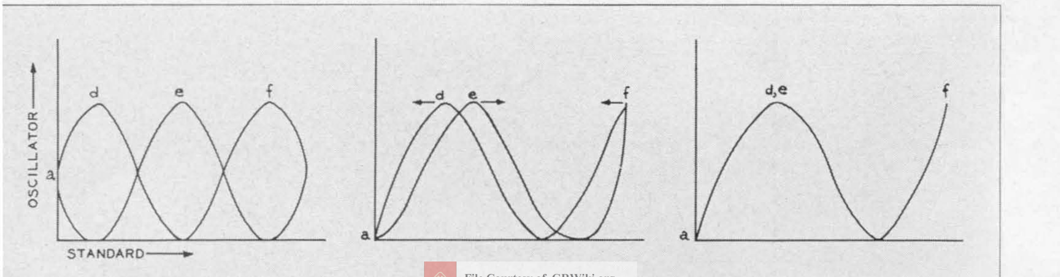
If the functions of identifying the frequency ratio and setting for exact frequency ratios are separated, then the effective range can be very greatly extended. For example, if patterns of the type shown in Figure 6 for integral frequency multiples are used, with a large horizontal deflection voltage (from the standard), the oscillator can easily be set at multiples of 1000, or more, to one. By using higher standard frequencies, identification of key points on the oscillator calibration can be made with simple patterns. Points can then be filled in for every kilocycle or even every half-kilocycle, using a 1-kc standard. The arrangement is illustrated in Figure 8.

When the horizontal deflection voltage is increased, the central section of the pattern only is observed. This pattern appears as a few cycles of two

---

*For detailed descriptions of patterns see, for example, Merwyn Bly, "A Guide to Cathode-Ray Patterns," John Wiley & Sons, Inc., 1943.

FIGURE 6. Lissajous pattern for a 3:1 frequency ratio.



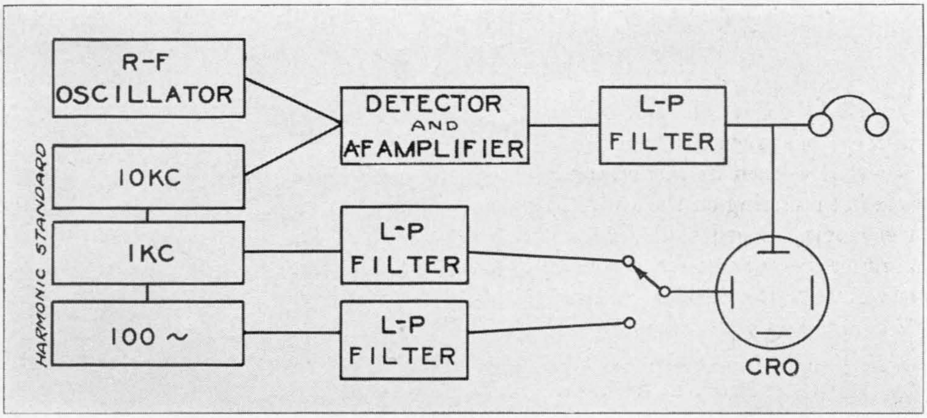
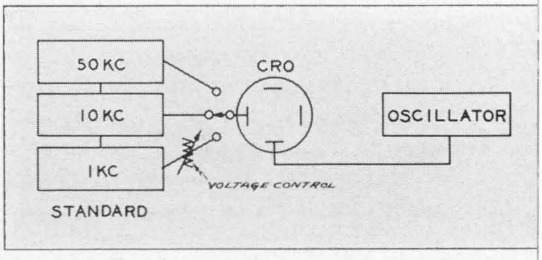


FIGURE 7. Block diagram of audio beat system for obtaining small calibration intervals.

waves, one progressing from left to right, the other from right to left, due to the forward and return traces caused by the sinusoidal sweep voltage. When stationary, the oscillator frequency is an exact integral multiple of the standard frequency. The $(n + \frac{1}{2})$:1 patterns appear as two chains, one moving to the right and one to the left. Higher ratio patterns are recognizable and can be used if desired.* A typical pattern is shown in Figure 9.

In some cases, the use of very high multiples of a given standard frequency will not extend the calibration to sufficiently high frequencies because of the difficulty of opening out the pattern for easy identification of the multiples of the standard frequency. By using a detector or receiver as in Figure 7, with comparatively high frequency standard harmonics, the very small frequency intervals can be set using the cathode-ray oscillograph in the audio, instead of radio, frequency range.

FIGURE 8. Block diagram of system for spreading out pattern to obtain small calibration intervals.



The oscillator under calibration, the standard frequency source, and the detector system are, in effect, a beat frequency oscillator, which in turn is calibrated by the audio-frequency checking system. In the intervals between the radio-frequency harmonics of the standard, the oscillator can be set to any multiple of the standard audio frequencies, and, with the cathode-ray oscillograph, just as readily to multiples of one half of these frequencies. In terms of the standard frequency values given in Figure 7, this means that the oscillator could be calibrated easily to every 50 cycles in its radio-frequency range.

—J. K. CLAPP

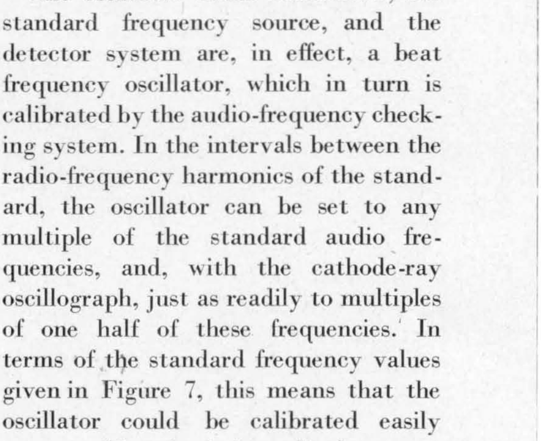


FIGURE 9. Appearance of pattern when oscillator being calibrated is set very nearly to a high multiple of a standard frequency. One trace appears to move slowly to the right; the other slowly to the left, as indicated by the arrows.

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*F. R. Stansel, Journal of the Institution of Electrical Engineers (British), June, 1943, p. 73.

THE WAR HAS BROUGHT ITS GRIEFS TO GENERAL RADIO

● THROUGHOUT THE AGES history has recorded the courageous deeds of women in warfare and in the relief of suffering on the battle front. In the coming decades historians will no doubt expound upon the contributions of women to the present world-wide conflict and will rightfully emphasize the important share in the final victory won by our women, both in the armed services and in industry.

About a year ago so many of the younger members of the General Radio organization had left us to join the armed forces that a serious shortage of personnel arose in our testing, inspection, and certain manufacturing departments. Breaking a lifelong custom with some slight trepidation, it was happily decided to build up a corps of women employees for this work—a decision which has met with gratifying success.

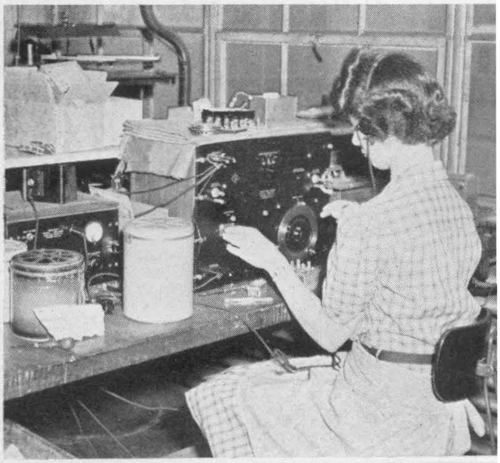
The Army has its WACS, the Navy its WAVES, the Coast Guard its SPARS, so it was but natural that General Radio should have its GRIEFS. The latter is a most inappropriate title in its literal meaning but, with a poetic license in spelling, is the inevitable contraction of General Radio Emergency Inspection Force.

A group of about a dozen girls were recruited for the initial GRIEF platoon to which were added two feminine members of our drafting department, one of whom is now on our Honor Roll as a Marine. The work which these young women were to do required some real knowledge of the theory and operation of our products, so that it became the happy privilege of the writer to have these young ladies in charge for a six-weeks' instruction period. The majority of the group had obtained more or less of a background of science and mathematics in high school, college, and ESMWT classes. Several of the girls held collegiate degrees but, what was far more important, all were anxious to stand behind husbands, sweethearts, and brothers in Bataan, in Africa, and on the high seas.

Guided by previous experience in teaching, the GRIEF class program started with a study of the fundamental principles of electrical science, first in d-c and then in a-c systems, and subsequently led into the manifold practical applications of this basic theory in the operation and testing of General Radio equipment. Several members of the engineering staff contributed valuable discussions concerning their specialized fields—lectures which served as material for a "graduation thesis" from each of the girls.

Morning sessions with ohms, farads, kilocycles, and rainbow-colored circuit diagrams in the classroom were followed by afternoons of graduated practice work in the inspection department. At the completion of the course the GRIEFS were ready to go into the testing and calibrating laboratory and really to hold their own in friendly competition with the masculine engineering assistants in this department. This training program clearly demonstrated the abilities of these enthusiastic young women to do this important work, and proved that some real knowledge of the subject matter considerably enhanced these abilities and heightened the personal satisfaction of the GRIEFS in their

THE GRIEFS AT WORK



work and accomplishments. Several of the girls had the ambition to supplement a full day in the laboratory with further evening courses in mathematics and radio.

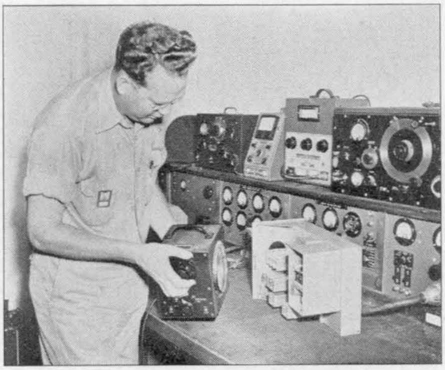
A most happy esprit de corps has developed between the GRIEFS and the heretofore lordly males, as demonstrated in lunchtime poker games, in certain activities of that legendary fellow with a bow and arrow, and in numerous other ways.

Since the first group of GRIEFS added pulchritude to precision in the General Radio laboratories, Uncle Sam has made further demands upon our masculine staff and to date four platoons of GRIEFS have successively joined our personnel to compensate for our expanding Honor Roll. Certain of these young ladies have found their talents and inclinations more adapted to manufacturing than to testing and inspection activities, so that they are now doing a grand job in the construction of precision mica capacitors and a multitude of other component parts.

War brings its suffering and sorrow to a nation, but to General Radio it has introduced a very special and enjoyable form of GRIEF.

—Horatio W. Lamson

MAINTENANCE WITH THE STROBOTAC



Manufacturers and users of radio communication equipment are finding increasing use for Strobotacs in design and maintenance work. This photograph, taken in the radio shop of the Eastern Air Lines at Miami, Florida, shows a vibrator power supply being studied with a General Radio Strobotac. Mechanical action of the reeds and contacts is observed under actual operating conditions. Trouble is diagnosed by correlation of mechanical data supplied by the use of the Strobotac with electrical data supplied by a cathode-ray oscillograph.

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THE General Radio EXPERIMENTER

VOLUME XVIII No. 6 NOVEMBER, 1943

ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also IN THIS ISSUE

GENERAL RADIO OPENS CHICAGO OFFICE

● **TO ASSIST USERS** of General Radio equipment in the Chicago and middle western area, the General Radio Company is opening a Chicago engineering office on December 1, 1943. The new office is located at 920 South Michigan Avenue, Chicago 5, and the telephone number is Wabash 3820.

In charge of this office is Lucius E. Packard who for the past three years has been in charge of the New York engineering office. Mr. Packard is a graduate of the Massachusetts Institute of Technology, receiving his Bachelor of Science degree in 1935. Previous to his assignment to the New York office, he was a member of the factory engineering staff and was engaged in both development and commercial engineering work.

Customers in and around Chicago are urged to make use of the facilities of this new office and to get in touch with Mr. Packard on all matters regarding General Radio equipment design and procurement. His experience in the application of our instruments and his close contact with factory production schedules should materially increase the efficiency with which we can serve our midwestern customers.

NEW YORK OFFICE

Succeeding Mr. Packard at the New York office is Martin A. Gilman of the factory engineering staff, a graduate of Massachusetts Institute of Technology in 1937 with the degree of Master of Science. Like Mr. Packard, he has been engaged in both development and commercial engineering work at the factory and is already well known in the New York area. As a reminder, the New York office address is Room 1504, 90 West Street, New York City, and the telephone number is Cortlandt 7-0850.

RESONANT VIBRATION IN LARGE ENGINE FOUNDATION

By G. M. DEXTER[1] and M. K. NEWMAN[2]

● **VIBRATION** in a large concrete foundation that was in near resonance with the gear mesh frequency of a pinion on a large Corliss engine was analysed recently with the aid of the vibration meter and sound analyser of the General Radio Company. The problem arose on mill engine No. 2 on the grinding tandem of the U. S. Sugar Corp., Clewiston, Florida. This grinding tandem consists of a set of revolving knives, a 2-roll crusher, and seven 3-roll, 78-inch mills. This tandem holds the world's record for its size in the amount of sugar cane crushed in 24 hours, namely about 7050 tons.

Engine No. 2 is a 36-inch by 60-inch Corliss engine that operates at 40 to 70 r.p.m., depending on the amount of sugar cane being crushed and its fiber content. Recent examination showed that its concrete foundation was vibrating badly and that the amount of vibration increased with the load on the grinding tandem and with the speed of the engine.

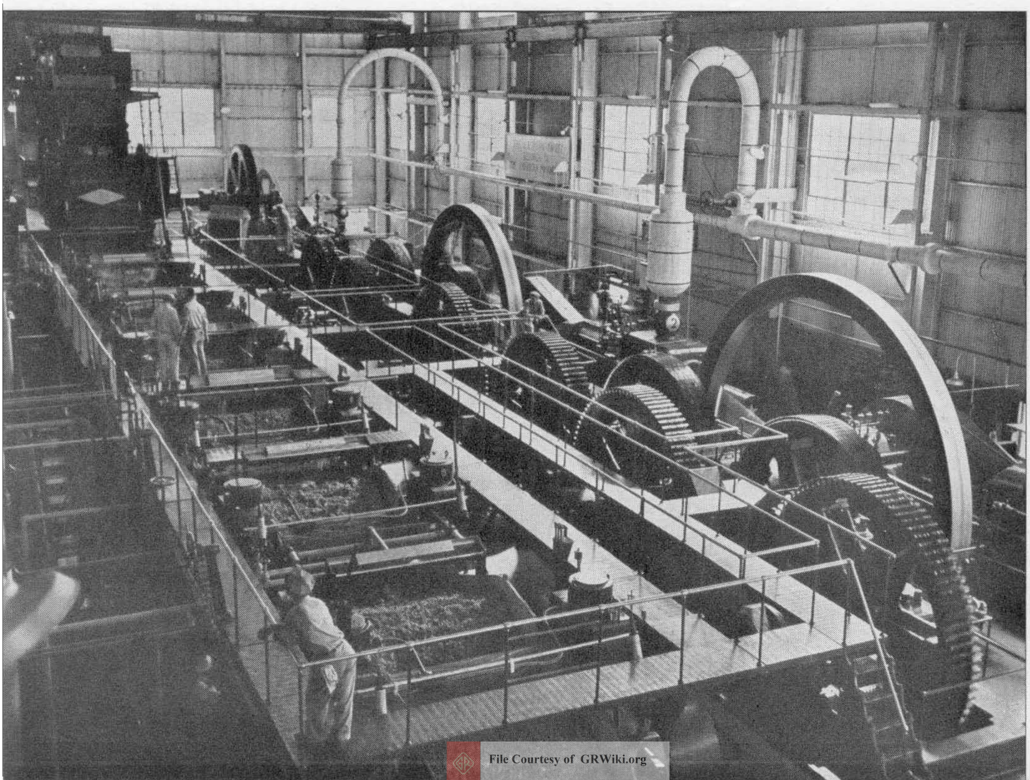
The engine is one of three on a large concrete foundation, about 145 ft. long, 40 ft. wide, and 11 ft. thick for over one-half its width. This engine drives three

---

[1] Engineer for Bitting, Inc., New York, N. Y., Supervisory Managers, U. S. Sugar Corp.

[2] Physics Dept., Columbia University, New York, N. Y.

FIGURE 1. The grinding tandem of the U. S. Sugar Corporation at Clewiston, Florida. Mill engine No. 2 is the center unit.

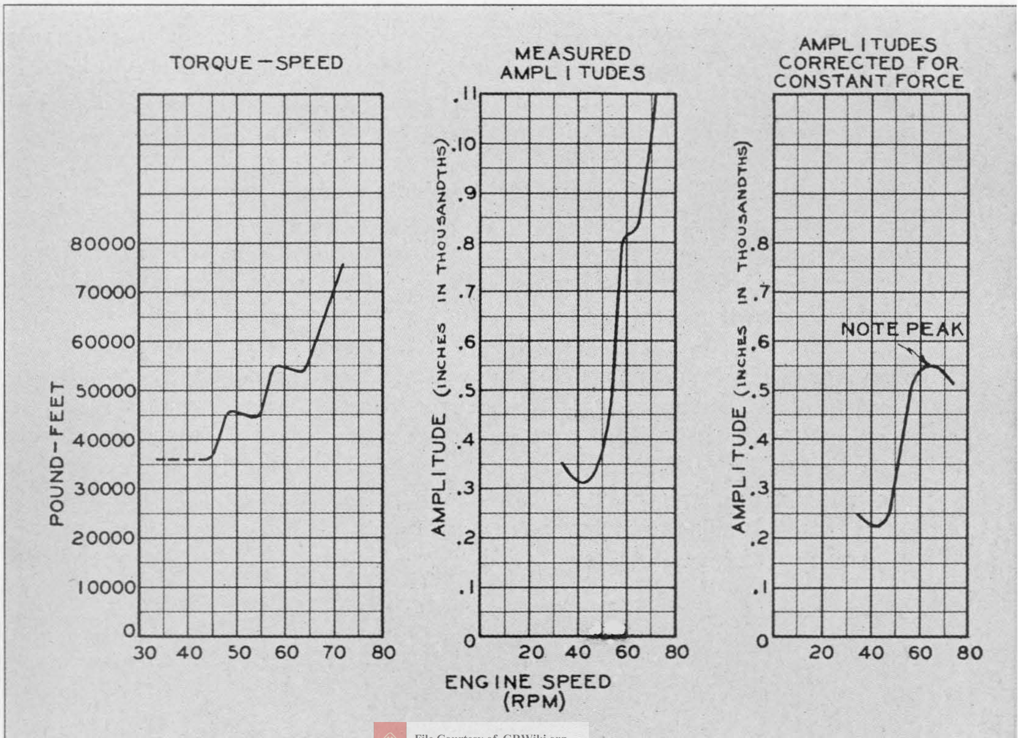


mills of the grinding tandem through a set of five large gears and three pinions. The foundation is on the typical muck on sand on porous rock of the Everglades where the water level is about three feet below the surface. The unusual nature of the soil made the problem more difficult. Although there is a definite friction against lateral movement of water, an irregular lateral movement does take place in the soil.

The first reaction to the vibration problem was that the concrete foundation by settling unequally was causing misalignment of gears that produced vibration. Four deep wells nearby were a part of the problem as they drew about 550 gallons per minute and caused a cone of depression in the ground water level that extended under the concrete foundation. Weekly level readings on various control points on the concrete foundation and ground water level were started to determine whether any settlement was actually taking place. An analysis of the load on the soil from the foundation and its machinery showed that the load was fairly well distributed and was about 0.8 tons per square foot. This amount is well within the limit that experience has shown to be safe for Everglades conditions where drainage ditches are in use.

While the preceding work was under way, a vibration meter and a sound or wave analyser of the General Radio Company were brought into use by Mr. M. K. Newman. He found that the vibration of the mill engine foundation could be broken down with the sound analyser into several frequencies, one of which was identical with the frequency of the gear mesh of the main pinion on engine No. 2, the others being multiples of this frequency. All

FIGURE 2. Compound amplitudes at engine No. 2 as measured on concrete foundation with TYPE 761-A Vibration Meter.



frequencies in the foundation varied with the speed of engine No. 2. The vibration meter permitted the determination of amplitudes of vibration, velocities, and accelerations due to each frequency. The frequency spectrum of the amplitudes showed that the most important effect was that due to the single-mesh frequency of the main pinion on engine No. 2. This vibration was found to exist throughout the foundation. A complete response characteristic of the foundation was taken up to the highest engine speeds used and a definite resonance peak was found for a constant vibrating force at a frequency corresponding to an engine speed of about 68 r.p.m.

The preceding fact immediately suggested that the pinion might be at fault. Measurements were taken that showed the pinion was in poor alignment with the two large gears it drove. Plaster of Paris casts of the teeth of the pinion and the two gears it drove showed they were worn.

A calculation of the foundation modulus by means of a method developed by M. A. Biot for an infinite beam on an elastic foundation (Journal of Applied Mechanics, May, 1937) and the use of methods outlined by S. Timoshenko in "Vibration Problems in Engineering" showed that the mill-engine foundation had several natural frequencies that were very close to frequency of the gear mesh of the main pinion on engine No. 2. The forced vibration problem was solved for a beam on an elastic foundation. The nine lowest modes of vibration were found to contribute appreciably to the resulting vibration, with the second harmonic in bending predominant because in near resonance. The resulting distribution of amplitude of vibration showed the same typical form that was obtained with a Davey Vibrometer. These data supported the conclusion reached with the instruments of the General Radio Company that the mill-engine foundation was in near resonance with the gear-mesh frequency of that pinion. In other words, the amplitudes of the vibration of the concrete foundation were greatly magnified.

The level readings also showed that two or three points near engine No. 2 on the foundation settled at high speeds of that engine but did not at low speeds. This fact is confirmation of the conclusion that settlement is due to vibration. Amplitude of vibration was a little more than 0.001 inches at a frequency of about 30 cycles per second.

In addition to the preceding, numerous other studies were made such as possible wabble of the flywheel of engine No. 2, possible loose foundation bolts in the base plate of the engine, stresses in gear teeth due to the heavy load on the grinding tandem, etc. A detailed discussion of all that was done is out of place here.

The meters of the General Radio Company were selected only after a definite search had been made for meters that could be used to analyse vibrations encountered in part from an unusual soil condition. Their successful application to this problem opens up a new field of investigation on the behaviour of concrete foundations under vibrating loads. This account is probably the first description of the application of the meters of the General Radio Company to a problem in the resonant vibration of a concrete foundation. With those meters, it was possible to analyse the problem so definitely that the cause and cure of the vibration could be given with considerable certainty.

MEASUREMENTS OF THE CHARACTERISTICS OF TRANSMISSION LINES

● **THE PROBLEM** of measuring the characteristics of transmission lines is frequently encountered both in the laboratory and in production testing. These measurements can be made conveniently on standard impedance-measuring equipment.

The methods in common use depend upon (a) the measurement of input impedance for various conditions of line termination or (b) the observation of voltage (or current) amplitude at input and output.

Input Impedance Methods

In terms of the so-called "telegraphist's equations" the behavior of a transmission line is defined by the characteristic impedance (usually designated as Z_O) and the complex propagation constant ($\gamma = \alpha + j\beta$). These two parameters of the line can be specified completely by two impedance measurements at the input to the line, one with the far end short-circuited, the other with the far end open-circuited. Designating these two impedances as Z_{SC} and Z_{OC}, respectively, we can write

$$Z_O = \sqrt{Z_{SC} Z_{OC}} \qquad (1)$$

$$\gamma l = \tanh^{-1} \sqrt{\frac{Z_{SC}}{Z_{OC}}} \qquad (2)$$

where l is the length of the line, in any convenient units.

A consideration of the variation of input impedance as the line length (or the frequency) is varied reveals that Z_O and γl can be obtained from certain specific (electrical) lengths. These lengths are the quarter wavelength (or its odd multiples) from measurements on which the attenuation constant (α) is readily deduced, and the eighth wavelength (or its odd multiples), from which the characteristic impedance is most accurately determined.

If both the frequency of measurement and the length of the sample are specified, the short- and open-circuit calculations involved, particularly for γl, are somewhat awkward. Measurements at specific lengths are more convenient and should be used if either the length or the frequency can be adjusted.

Attenuation Measurement at Quarter Wavelength

The input impedance of a line terminated in an impedance Z_T is given by

$$Z_{in} = Z_O \frac{Z_T \cosh \gamma l + Z_O \sinh \gamma l}{Z_T \sinh \gamma l + Z_O \cosh \gamma l} \qquad (3)$$

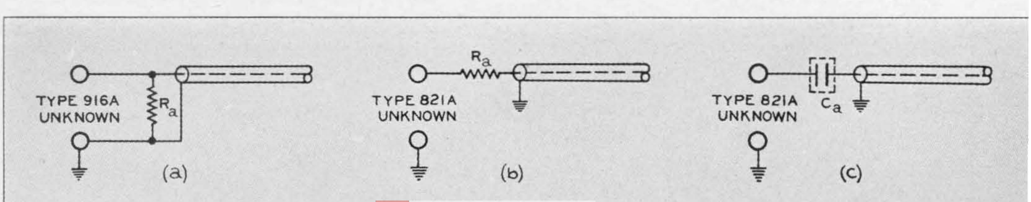
For a line one-quarter-wave long short-circuited at the receiving end ($\beta l = \frac{\pi}{2}$, $Z_T = O$) the input impedance is

$$Z_{SC} = Z_O \coth \alpha l \qquad (4)$$

For the same length of line with the end open-circuited, the input impedance is

$$Z_{OC} = Z_O \tanh \alpha l \qquad (5)$$

FIGURE 1. In (a) and (b) are shown the methods of using an auxiliary resistor to assist in locating the frequency of quarter-wave resonance, when the real component of the input impedance is outside the direct-reading range of the TYPES 916-A and 821-A, respectively; (c) shows the conventional series capacitor method for accurate measurement with the TYPE 821-A.



If $\alpha l \ll 1$, the input impedances can be written in the approximate form

$$Z_{SC} = \frac{Z_O}{\alpha l} \qquad Z_{OC} = Z_O \alpha l \tag{6}$$

The input impedances represented by (6) will have slight reactive components from the reactive component of $Z_O = R_O - jX_O$. Consequently, it is difficult to locate experimentally the true quarter-wave condition. Practically, however, no significant error will be introduced if either the condition of zero reactance or the condition of maximum input resistance is determined. The most convenient method to use will depend, to a certain extent, on the magnitude of the input resistance and upon the instrument used for measurement. Neglecting the effects of the reactive component, X_O, Equation (6) can be rewritten as

$$\alpha l = \frac{R_O}{R_{SC}} \qquad \alpha l = \frac{R_{OC}}{R_O} \tag{7}$$

Equation (7) yields accurate results for attenuation constant, as the quantities involved can be determined within a few per cent, and the formulae are valid to about the same accuracy for values of αl and $\frac{X_O}{R_O}$ small compared to unity.

Example of Attenuation Measurement

A length of concentric cable (General Radio Type 774), about 117 feet long, was found to have its quarter-wave resonance at a frequency in the vicinity of 1.25 megacycles. The input conductance for the shorted condition was found to be outside the direct-reading range of the Type 821-A Twin-T Impedance Measuring Circuit, and was measured by the methods indicated in Figure 1b. Although best accuracy is obtained by the use of an auxiliary series capacitor, as indicated in Figure 1c, the use of a series resistor simplifies the process of finding the resistance maximum.

The resistance maximum (conductance minimum) was located at 1.26 mc and found to be approximately 1325 ohms from the series resistance method. A more nearly accurate measurement using the series capacitor method[1] gave an input resistance of 1370 ohms.

The characteristic resistance, R_O, as determined from measurements described later, is about 72.5 ohms. Then, from Equation (7) we have

$$\alpha l = \frac{72.5}{1370} \text{ nepers} = 0.0528 \text{ nepers}$$

The attenuation constant at this frequency is, therefore, 0.211 nepers (1.83 db) per wavelength.[2]

The same cable was measured on the Type 916-A Radio-Frequency Bridge for the short-circuit condition. A substitution method[3] as indicated in Figure 1a was used. The data observed were:

$R_1 = 580$ ohms (connection as shown)

$R_2 = 998$ ohms (cable disconnected)

$$R_{in} = \frac{580 \times 998}{995 - 580} = 1380 \text{ ohms}$$

A measurement was also made for the open-circuit condition on the same length of cable, using the Type 916-A. This measurement is particularly convenient, as the input resistance is within

---

[1] Described in detail in instruction book for Type 821.

[2] One neper = 8.686 decibels.

[3] The use of a parallel capacitor is normally recommended. The parallel resistor method, however, is somewhat more convenient in use, and for this particular measurement leads to about the same final accuracy.

the direct-reading range of the bridge. The observed input resistance was 3.68 ohms[4], from which

$$\alpha l = \frac{3.68}{72.5} = 0.0507 \text{ nepers}$$

The check between the two values of αl obtained by different methods of measurement is seen to be within ±2%.

Comparing the two instruments, the Type 916-A is found to have a definite advantage over the Type 821-A for the following reasons.

(a) The initial balance is virtually independent of frequency, and the frequency of maximum (or minimum) resistance can be located more readily.

(b) The resistance dial calibration is independent of frequency, somewhat simplifying the computations.

Characteristic Impedance Measurement by Open- and Short-Circuit Measurements

The optimum length of line on which to make open- and short-circuit impedance measurements is an eighth wavelength. At this length the magnitudes of the two impedances are approximately equal, with reactive components of opposite sign. Also, the resistive component is small, and very little error is introduced by considering only the reactive component. As an example, the following observations were made on the piece of cable previously discussed, at a frequency of 0.63 megacycles.

$$Z_{SC} = 7 + j\,73.0 \text{ ohms}$$

$$Z_{OC} = 2.5 - j\,71.4 \text{ ohms}$$

$$\begin{aligned} Z_O &= \sqrt{Z_{SC}Z_{OC}} \\ &= \sqrt{(7 + j\,73.0)(2.5 - j\,71.4)} \\ &= \sqrt{5238 - j\,318} \\ &= \sqrt{5238}\sqrt{1 - j\,0.061} \\ &= 72.3 - j\,2.1 \text{ ohms} \end{aligned}$$

If the reactance components only of Z_{SC} and Z_{OC} were taken, the *magnitude* of the characteristic impedance so calculated would differ by only a few tenths ohm from the correct value.

The Type 916-A is particularly convenient for the eighth wavelength measurement, inasmuch as both components fall within the direct-reading range of the bridge, for either condition of termination.

The short- and open-circuit impedance measurements can equally well be made on the Type 821-A, with the advantage that the reactance component is determined from the readings of a precision condenser which has an accuracy of ±0.1%. The Type 821-A, however, has the disadvantage that the input reactance cannot be measured directly at lower frequencies, and an external series capacitor must be used.

The effective input capacitance of the eighth-wave line depends, of course, upon the frequency. The approximate

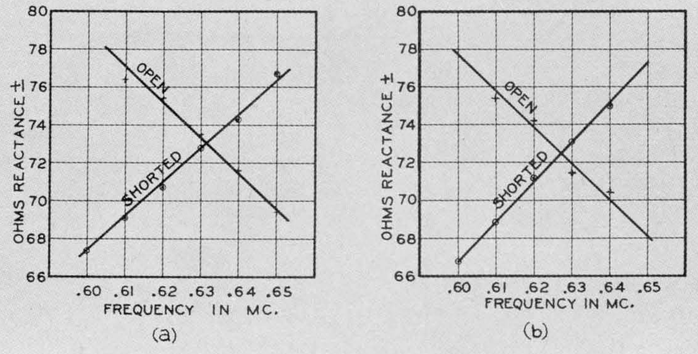


Figure 2. Plots showing the variation of input reactance in the vicinity of the eighth wavelength as observed with (a) the Type 916-A and (b) the Type 821-A. The intersection gives accurately the real component of the characteristic impedance, provided $(\alpha l)^2 << 1$.

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[4] The absolute accuracy limitation of the Type 916-A has been set as 0.1 ohm. The value of 3.68 is therefore subject to an uncertainty of the order of 3%.

value of the effective input capacitance at any frequency can readily be estimated, as the order of magnitude of the characteristic impedance is usually known. We may write

$$X_{in} \approx \pm Z_O = \frac{1}{\omega\hat{C}} \qquad (8)$$

where $\hat{C}$ is the effective input capacitance and may be positive or negative.[5] If the typical value of 70 ohms is taken for Z_O, the effective capacitance becomes approximately

$$\hat{C} \approx \frac{2300}{f}$$

where $\hat{C}$ is in μμf and f in megacycles.

For any frequency lower than about two megacycles, this capacitance is outside the direct range of the 821 (1000 μμf) and a substitution method must be resorted to using a series capacitor. The method is illustrated in Figure 1c, and the input reactance can be expressed directly in terms of observed data as[6]

$$X = \pm \frac{159{,}200}{fCC_a}(C_a - C) \qquad (9)$$

In this expression C is the observed capacitance with the connection as shown in Figure 1c, C_a the value obtained when the cable input is shorted, and f the frequency in megacycles.

Examples of Measurement

The eighth-wavelength frequency for the section of cable already discussed is about 0.63 megacycle. At this frequency the input capacitance of the open-ended line is about 3500 μμf, from Equation (8). An auxiliary series capacitor of about 700 μμf was used, and the following data obtained

$$f = 0.63 \text{ mc}$$
$$C = 588.5\ \mu\mu\text{f}$$
$$C_a = 709.7\ \mu\mu\text{f}$$
$$X_{in} = \frac{(159{,}200)(709.7 - 588.5)}{(0.63)(588.5)(709.7)} = 73.3 \text{ ohms}$$

For the short-circuit condition, at the same frequency, the data were

$$C = 372.8\ \mu\mu\text{f}$$
$$C_a = 336.6\ \mu\mu\text{f}$$
$$X_{in} = 72.8 \text{ ohms}$$

In Figure 2 is shown a plot of the observed input reactance for both short- and open-circuit conditions over a narrow range of frequency in the neighborhood of the $\frac{\lambda}{8}$ frequency.

The equations and computations just presented have neglected the real components of the input impedances. Taking them into account (following the method of computation outlined in the instruction book for the TYPE 821-A) the results were

$$Z_{SC} = 7.0 + j\,72.8$$
$$Z_{OC} = 2.8 - j\,73.2$$

As with the data cited for the TYPE 916, the neglect of the resistive component affects the magnitude of the calculated Z_O by a negligible amount.

— IVAN G. EASTON

(To be continued)

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[5] It is convenient to refer to negative input capacitance as the measuring circuits use capacitance standards.

[6] This expression is valid only if the resistive component of the input impedance is small compared to the reactive component. This condition is satisfied at the eighth wavelength.

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ELECTRICAL MEASUREMENTS AND THEIR INDUSTRIAL APPLICATIONS

Also

IN THIS ISSUE

MEASUREMENTS OF THE CHARACTERISTICS OF TRANSMISSION LINES

PART II

IMPEDANCE MEASUREMENT ON TERMINATED LINE

● **POSSIBLY THE SIMPLEST METHOD** of determining the characteristic impedance is to terminate a quarter-wave section of line in a variable resistance, to measure the input resistance with the Type 916-A Radio-Frequency Bridge, and to adjust the terminating resistance until the input and terminating resistances are equal. The value of resistance at which the two are equal is exactly the characteristic impedance, in the ideal case of a loss-free line terminated in a pure resistance. Attenuation in the line and reactance in the termination modify the behavior slightly, in accordance with the following approximate expression:

$$R_{\mathrm{in}} \approx R_0 \left[1 - \left(\frac{X_0 + X_T}{R_{\mathrm{in}}} \right)^2 \right] \tag{10}$$

in which X_0 and X_T are the reactive components of the characteristic impedance and the terminating impedance, respectively. For the condition $\left(\frac{X_0 + X_T}{R_0} \right)^2 << 1$, Equation (10) may be written as

$$R_0 \approx R_{\mathrm{in}} \left[1 + \frac{1}{2} \left(\frac{X_0 + X_T}{R_{\mathrm{in}}} \right)^2 \right] \tag{11}$$

The effect of X_0[7] on Equation (11) is negligible for lines having reasonably low-loss insulation, at frequencies of the order of a megacycle. The effect of X_T[7], however, may easily make the correction term of (11) become a few per cent.

The reactive component of a decade resistance box, such as might

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[7] X_0 is capacitive in nature but Equation (11) is so written that the positive numerical value is to be used. The sign of X_T should be positive for inductive reactance in the termination and negative for capacitive reactance.

be used for the variable termination, is almost invariably inductive in nature, at the values of resistance required for this type of measurement. It is therefore a relatively simple matter to reduce the net reactance of the termination to a negligible value by connecting in series a fixed capacitor of appropriate size.

Example of Measurement

The 117-foot length of TYPE 774 Cable was terminated in a TYPE 602 Decade-Resistance Box. The input resistance was measured on the TYPE 916-A Radio-Frequency Bridge, at 1.26 megacycles, the previously determined quarter-wave frequency. The input and terminating resistances were found to be equal for a 71.2 ohm setting of the decade box. This value, to a first approximation, corresponds to the characteristic impedance of the line.

The series reactance (X_T) of the decade box was measured directly on the bridge and found to be 10.3 ohms. X_0, the reactive component of Z_0, was known from previous measurements to be about 2.1 ohms. Inserting these values in Equation (11), the characteristic resistance is

$$\begin{aligned} R_0 &= 71.2\left[1 + \left(\frac{2.1 + 10.3}{71.2}\right)^2\right] \\ &= 71.2\ [1 + 0.0152] \\ &= 72.3 \text{ ohms} \end{aligned}$$

The value of X_0 will, of course, not be known unless independent measurements are made. If it is neglected in Equation (11), the indicated value of R_0 is 72.0 ohms.

As a check on the method and on the validity of Equation (11), a capacitor having approximately 10 ohms reactance was connected in series with R_T, to reduce to a negligible value the effective value of X_T. The input and terminating resistances were then found to be equal for a setting of 72.2 ohms. The agreement with the corrected value obtained from the first measurement is excellent.

The direct-reading accuracy of the resistance dial of the TYPE 916-A is 1%. If measurements to an accuracy better than 1% are required, a correction factor for the dial reading must be determined. The correction factor may be obtained by measuring known resistors, whose values lie reasonably near the unknown value to be measured.

The data given for the two measurements just described were corrected by checking the bridge against TYPE 500 Resistors, whose resistance values are known to within a few tenths per cent at the frequency of measurement. The correction was within the nominal 1% accuracy and amounted to only a few tenths ohm.

Attenuation Measurement from Standing-Wave Ratio

The ratio of input voltage to output voltage on an open-circuited transmission line is given by

$$\frac{V_{\text{in}}}{V_{\text{out}}} = \cosh \alpha l \cos \beta l + j \sinh \alpha l \sin \beta l \qquad (12)$$

If the length of line, l, corresponds to an odd multiple of a quarter-wavelength, we have $\cos \beta l = 0$, $\sin \beta l = \pm 1$ and Equation (12) reduces to

$$\frac{V_{\text{in}}}{V_{\text{out}}} = \pm j \sinh \alpha l \qquad (13)$$

Considering magnitude only and assuming that αl is small compared to unity, Equation (13) can in turn be written as

$$\left|\frac{V_{\text{in}}}{V_{\text{out}}}\right| \approx \alpha l \qquad (14)$$

The true condition of quarter-wave resonance is difficult to establish experimentally, but with low-loss lines no significant error is introduced if the condition of maximum voltage rise is used instead.

The condition of maximum voltage rise can be determined experimentally with a variable frequency oscillator, or signal generator, and a vacuum-tube voltmeter. Both the input and output voltages on the line will vary with frequency and the ratio of the two voltages must theoretically be taken at several frequencies to determine the maximum value. Practically, the correct frequency can be located quite accurately by adjusting for the *minimum* value of *input* voltage since the line input impedance goes through a minimum at this frequency.

Effect of Harmonics

The experimental difficulty with the voltmeter method lies in the possible serious errors that may be encountered from harmonic distortion in the voltage source. This type of error depends on the impedance of the source, as well as on the harmonic content of the voltage. At the frequency corresponding to quarter-wave resonance, the cable input impedance is extremely low so that V_0 at this frequency is small. At the second harmonic frequency, however, the input impedance is high, as the line is in approximate half-wave resonance at the double frequency. Consequently, the applied fundamental voltage is lower than on open-circuit while the second-harmonic voltage is about the same as on open-circuit. The lowered fundamental voltage is stepped up to the cable output by the resonant rise in the line and the second-harmonic voltage at the line output is essentially equal to the second-harmonic voltage at the line input. Under these circumstances the harmonic content of the input and output voltages will differ and the observed voltage ratio may be seriously in error.[8] The magnitude of the error introduced depends upon the ratio of the generator impedance to the characteristic impedance of the line, and upon the type of response of the voltmeter, that is, peak reading, r-m-s, or average.

Difficulties from harmonic distortion can, of course, be avoided by the use of a tuned voltmeter. A radio receiver may also be used, if means are available for calibrating its sensitivity.

Effect of Voltmeter Loading

The finite input resistance of the vacuum-tube voltmeter may, of course, reduce the resonant rise, and the input capacitance may shift the frequency of quarter-wave resonance. The latter effect is negligible at low frequencies. For example, the input capacitance of the TYPE 726-A Vacuum-Tube Voltmeter is approximately 6 $\mu\mu$f, while the total capacitance of a quarter-wave section of line at one megacycle may be several thousand micromicrofarads.

The effect of the resistive loading of the line by the voltmeter depends upon the ratio of the voltmeter resistance to the output resistance at the open end of the line. At a frequency of one megacycle the input resistance of the TYPE 726-A Vacuum-Tube Voltmeter is greater than one megohm. The output resistance of a typical line in quarter-wave resonance at this frequency will be very much less

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[8] An experimental observation with a 1500-ohm generator feeding a 75-ohm cable yielded a resonance rise ratio $\frac{V_{\text{out}}}{V_{\text{in}}}$ of 4, whereas the known correct value was 20.

than one megohm, and the voltmeter loading can be neglected.

Examples of Measurement

The resonant rise in the quarter-wavelength of TYPE 774-A Cable was measured, using a TYPE 805-A Standard-Signal Generator as the voltage source, and a TYPE 726-A Vacuum-Tube Voltmeter as the voltage indicator. The minimum ratio of V_{in} to V_{out} was found to be 0.0464 and occurred at a frequency of 1.26 megacycles. The indicated value of αl is almost 20% lower than that obtained from the quarter-wave input-resistance measurement previously described. A part of this discrepancy was traced to the effects of temperature on the attenuation constant (the voltage-rise measurement was made at an ambient temperature nearly 20° F. lower than the input-resistance measurement) and the rest is assumed to be due to the effects of harmonics on the voltage-rise measurement.

Velocity of Propagation

The imaginary component (β) of the complex propagation constant is frequently specified in terms of v, the velocity of phase propagation. The relationship is given by

$$\beta = \frac{\omega}{v} = \frac{2\pi}{\lambda} \tag{15}$$

The velocity of propagation can be deduced from observations on the resonant lengths of the line, using the following relationships. The ratio of the velocity on the line (v_l) to the free-space velocity (v_s) is equal to the corresponding ratio of wavelengths (λ_l and λ_s), at any given frequency.

$$\frac{v_l}{v_s} = \frac{\lambda_l}{\lambda_s} \tag{16}$$

But λ_s, the free-space wavelength, can be expressed in terms of frequency as

$$\lambda_s = \frac{300}{f} \tag{17}$$

where f is in megacycles and λ_s in meters.

From (17) and (16) we may write the ratio[9] of velocity on the line to velocity in space as

$$\frac{v_l}{v_s} = \frac{\lambda_l f}{300} \tag{18}$$

In Equation (18) λ_l is the wavelength in meters on the line at a frequency f megacycles.

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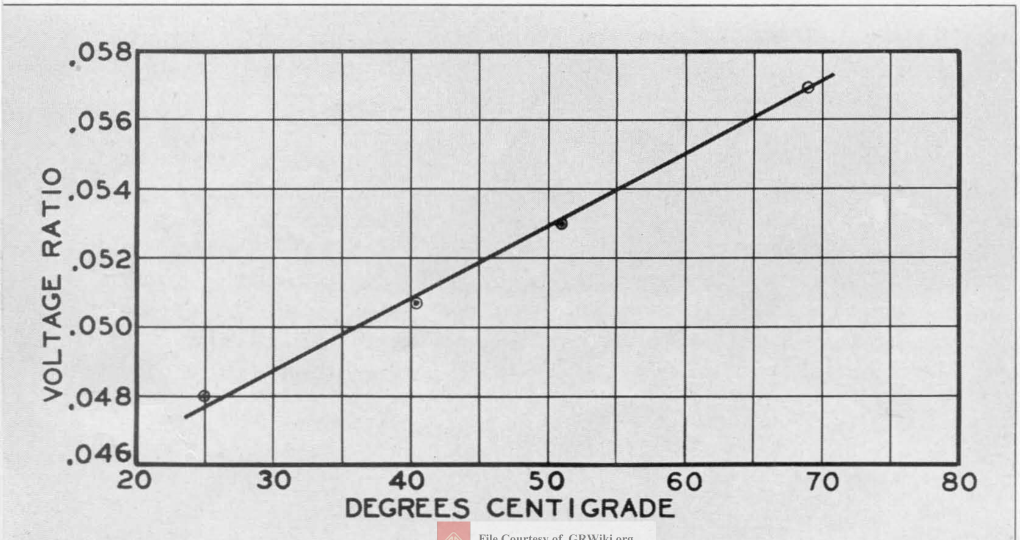
[9] v is usually specified as a percentage or fraction of free space velocity, rather than an absolute value.

FIGURE 3. Plot of the variation with temperature of the observed ratio of input voltage to output voltage on the open-circuited section of a line in quarter-wave resonance.



Since it will usually be more convenient to determine the quarter-wavelength (or some odd multiple thereof) rather than the full wavelength, λ_l, let us rewrite (18) as

$$\frac{v_l}{v_s} = \frac{l}{300n} f \qquad (19)$$

where l is the length in meters, f the frequency in megacycles, and n the ratio of line length to wavelength. For the quarter-wave line, we have

$$\frac{v_l}{v_s} = \frac{lf}{75} \qquad (20)$$

or if l is in feet

$$\frac{v_l}{v_s} = \frac{lf}{246} \qquad (21)$$

The condition of quarter-wave resonance required for the above equations may be determined by bridge measurements or from voltage-rise observations. (A reaction method is frequently recommended for indicating resonance, but has the disadvantage that most commercially available oscillators or signal generators have a buffer amplifier between oscillator and output, so that no reaction on oscillator plate or grid current can be obtained.)

Characteristic Impedance from Resonant Frequency and Capacitance

The velocity is related to the inductance and capacitance (L and C) per unit length of line by the approximate expression

$$v \approx \frac{1}{\sqrt{LC}} \qquad (22)$$

which can be written as

$$v \approx \frac{1}{CZ_0} \qquad (22a)$$

From Equation (22a) the characteristic impedance can be determined if the velocity of propagation and the capacitance per unit length are known. The capacitance can be measured directly on the Type 821-A Twin-T Impedance-Measuring Circuit, provided a sufficiently short length is used so that resonance effects are insignificant. The length used should not exceed about 1/10 of a quarter-wavelength, if accurate results are desired. (At a line angle of 10°, the effective input capacitance differs by 1% from the static value.)

The characteristic impedance can be expressed directly in terms of the frequency of quarter-wave resonance and total line capacitance as

$$Z_0 = \frac{1}{4C_0 f} \qquad (23)$$

Example of Measurements

The capacitance of approximately six feet of the Type 774-A Cable was measured at 1.26 Mc (the previously determined quarter-wave resonant frequency for the 117-foot length) and found to be 134.0 $\mu\mu$f. At 1000 cycles the capacitance was measured as 143.4 $\mu\mu$f. The total capacitance of the 117-foot length at 1000 cycles was 2954 $\mu\mu$f. Consequently, the total capacitance of 117 feet at 1.26 Mc can be computed as

$$C_0 = 2954 \times \frac{134.0}{143.4} = 2760\ \mu\mu\text{f}$$

Inserting these values in Equation (23) we have

$$Z_0 = \frac{10^6}{4 \times 1.26 \times 2760} = \underline{\underline{71.9 \text{ ohms}}}$$

Summary

In the table following are summarized the results obtained by the various methods of measurement described.

TABLE I

Method	*Instrument*	Z_0
Open- and short-circuit impedance	TYPE 821-A Twin-T Impedance-Measuring Circuit	73.0 — j2.1 ohms
Open- and short-circuit impedance	TYPE 916-A Radio-Frequency Bridge	72.3 — j2.1 ohms
Resistance-Termination	TYPE 916-A Radio-Frequency Bridge	72.3 ohms (corrected for reactance of terminating resistance)
Resistance-Termination with capacitor in series with terminating resistance	TYPE 916-A Radio-Frequency Bridge	72.2 ohms
Capacitance and Resonant Frequency	TYPE 821-A Twin-T Impedance-Measuring Circuit, TYPE 716-A Capacitance Bridge, TYPE 805-A Standard-Signal Generator, TYPE 726-A Vacuum-Tube Voltmeter	71.9 ohms

It should be noted that in all the methods described for the determination of characteristic impedance, with the exception of the resistance-termination method, the frequency of measurement enters directly into the calculations. If the maximum accuracy of the measuring instruments is to be realized, the frequency must accordingly be known accurately, preferably to within 0.1%.

The measurements described in this article were made using oscillators and signal generators whose standard accuracy of frequency calibration is ±1%. More accurate frequency measurements were not made as it was desired to determine the consistency of results that would be obtained with standard laboratory equipment. The results obtained by the four different methods of measurement are seen to agree with a spread of less than 2%.

Uniformity

If the transmission line is not uniform in its characteristics or has discontinuities in construction, the observed value of Z_0 may depend upon the direction of propagation. For the particular section of cable on which observations were made, a difference of 1.2 ohms was noted, when the measurement was made by the open- and short-circuit impedance method. By the resistance termination method, the same value was obtained for either direction of propagation.

— IVAN G. EASTON

This is the second of a series of two articles by Mr. Easton dealing with transmission line measurements. The first appeared in the November issue of the EXPERIMENTER.

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544-P3	A-C Power Supply
561-D	Vacuum-Tube Bridge
605-A,-B	Standard-Signal Generator
608-A	Oscillator
614-C	Selective Amplifier
616-D	Heterodyne Frequency Meter
617-C	Interpolation Oscillator
620-A	Heterodyne Frequency Meter and Calibrator
625-A	Bridge
631-A,-B	Strobotac
636-A	Wave Analyzer
648-A	Strobolux
650-A	Impedance Bridge
667-A	Inductance Bridge
684-A	Modulated Oscillator
690-C	Piezo-Electric Oscillator
691-C	Temperature-Control Box
692-B	Multivibrators
693-B	Syncronometer
694-C	Control Panel
698-A	Duplex Multivibrator
700-A	Wide-Range Beat-Frequency Oscillator
707-A	Cathode-Ray Null Detector
713-A	Beat-Frequency Oscillator
713-B	Beat-Frequency Oscillator
714-A	Amplifier
715-A	Direct-Current Amplifier
716-A	Capacitance Bridge
716-B	Capacitance Bridge
723-A,-B,-C,-D	Vacuum-Tube Fork
726-A	Vacuum-Tube Voltmeter
727-A	Vacuum-Tube Voltmeter
729-A	Megohmmeter
731-A	Modulation Monitor
731-B	Modulation Monitor
732-A	Distortion and Noise Meter
732-B	Distortion and Noise Meter
733-A	Oscillator
736-A	Wave Analyzer
740-B	Capacitance Test Bridge
740-BG	Capacitance Test Bridge
757-A	U-H-F Oscillator
759-A	Sound-Level Meter
759-B	Sound-Level Meter
760-A	Sound Analyzer
761-A	Vibration Meter
769-A	Square-Wave Generator
775-A	Frequency-Limit Monitor
804-A	U-H-F Signal Generator
804-B	U-H-F Signal Generator
805-A	Standard-Signal Generator
821-A	Twin-T Impedance-Measuring Circuit
834-B	Electronic Frequency Meter
913-A	Beat-Frequency Oscillator
—	Variacs (all types)

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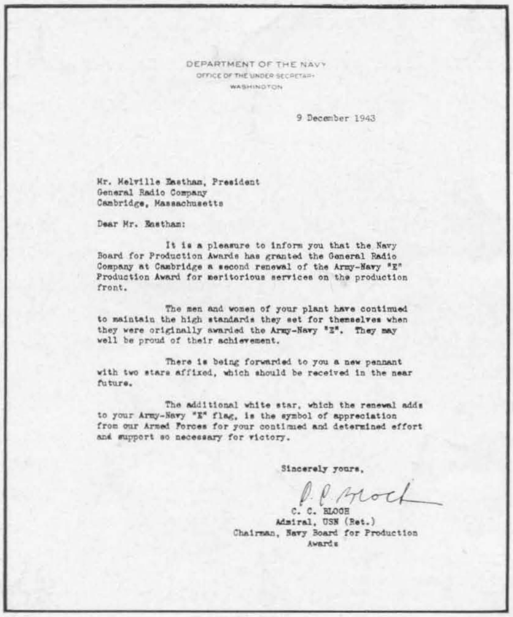
The accompanying letter from the Navy's Board of Production Awards speaks for itself. Needless to say, we at General Radio are proud that our efforts have won a second renewal of the "E." To all in other organizations whose co-operation has helped us to keep up our production record we express our sincere appreciation.



DEPARTMENT OF THE NAVY
OFFICE OF THE UNDER SECRETARY
WASHINGTON

9 December 1943

Mr. Melville Eastham, President
General Radio Company
Cambridge, Massachusetts

Dear Mr. Eastham:

It is a pleasure to inform you that the Navy Board for Production Awards has granted the General Radio Company at Cambridge a second renewal of the Army-Navy "E" Production Award for meritorious services on the production front.

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There is being forwarded to you a new pennant with two stars affixed, which should be received in the near future.

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Sincerely yours,

C. C. Bloch
C. C. BLOCH
Admiral, USN (Ret.)
Chairman, Navy Board for Production
Awards

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