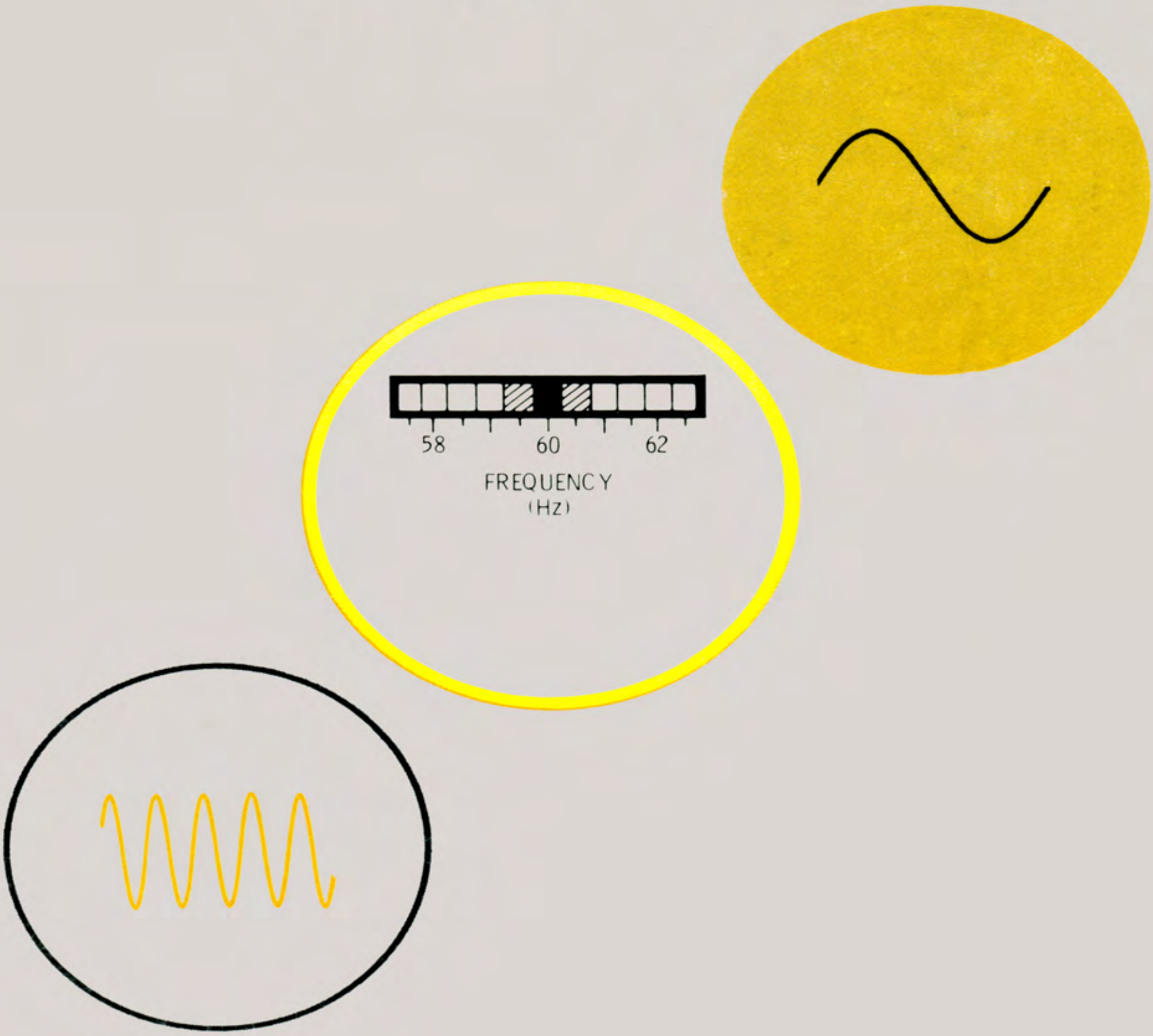
Howard W. Sams PUBLICATION 21179

FREQUENCY and Its MEASUREMENT

by
Rufus P. Turner



FREQUENCY

AND ITS

MEASUREMENT

by

Rufus P. Turner, Ph.D.

HOWARD W. SAMS & CO., INC.
THE BOBBS-MERRILL CO., INC.
INDIANAPOLIS • KANSAS CITY • NEW YORK

FIRST EDITION

FIRST PRINTING—1975

International Standard Book Number: 0-672-21179-3
Library of Congress Catalog Card Number: 75-27451

Preface

Frequency is perhaps the property most often associated with every ac phenomenon. It is also the unique characteristic that distinguishes the radio spectrum from the audio spectrum, and heat from light, and it accounts for the difference between X-rays, gamma rays, and the various colors of light. Frequency can be measured and/or controlled with some of the greatest precision known in the world of applied science. Through use of an atomic frequency standard, for example, the National Bureau of Standards maintains the frequency of transmissions from stations WWV and WWVH with an accuracy of ±2 parts per 100 billion.

This book offers a brief introduction to the subject of frequency and provides a survey of frequency-measurement methods. It is addressed to the reader who already knows practical electronics and who desires a more comprehensive view of frequency than is provided by the average textbook of general electronics. The presentation is mostly practical and therefore essentially nonmathematical. Supplementary information is offered by the appendixes.

It is hoped that this book will ease the task of the technician who must occasionally measure frequency and would like to select the most suitable method for a particular instance.

RUFUS P. TURNER

Contents

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

CHAPTER 1

FUNDAMENTALS

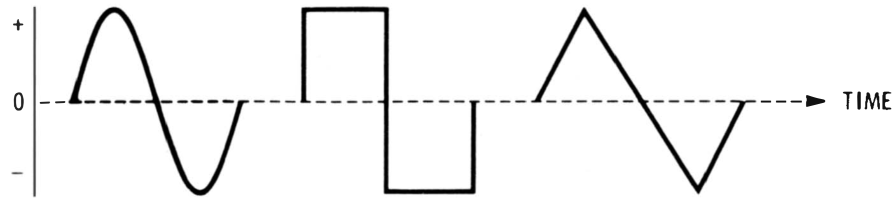
This chapter offers an introduction to the subject of frequency and a spot review of those alternating-current fundamentals needed by anyone dealing with frequency. The known range of frequencies generated by man and by nature is wide indeed. Some notion of this tremendous scope can be gained from this chapter, even if our immediate concern in electronics is with the frequency of alternating electric currents and voltages.

For a broader view of related theory, the reader may consult the chapters on alternating currents and on electromagnetic radiation in standard textbooks of electrical engineering and physics.

1.1 BASIC DEFINITION

The term *frequency* (symbol, f) has different meanings in different fields. In the electrical sciences, however, this term denotes the number of times in one second that an alternating current or voltage repeats a complete cycle.[1] A complete cycle is usually understood to be the single, uninterrupted sequence of changes that a current or voltage goes through as it starts from zero, reaches a maximum positive value, returns to zero, reaches a maximum negative value, and finally returns to zero.

[1] *Frequency* is used sometimes to mean the number of electrical pulses per second, but the specific term *pulse-repetition rate* (abbreviated *prr*) or *pulse-repetition frequency* (abbreviated *prf*) usually is preferred.

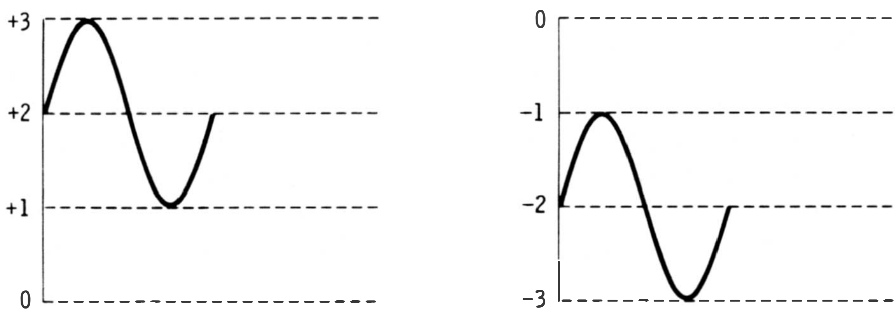


(A) Sine wave. (B) Square wave. (C) Triangular wave.

Fig. 1-1. Typical single ac cycles.

Such a single, complete cycle is illustrated by Fig. 1-1 (Fig. 1-1A for a sine wave, Fig. 1-1B for a square wave, and Fig. 1-1C for a triangular wave). The cycle may have any waveform whatever and may be symmetrical or asymmetrical. Unlike the situation in Fig. 1-1, a cycle may also have its negative peak first and its positive peak last.

Often, a cycle does not begin and end at zero at all, but at some definite value of current or voltage, as shown in Fig. 1-2. In Fig. 1-2A, the cycle swings between +1 and +3 (volts or amperes), with +2 as the mean value or *reference level;* in Fig. 1-2B, it swings between −1 and −3 (volts or amperes), with −2 as the mean value. Such a quantity is properly called an *alternating component* or *ac component.* It is also called a *fluctuating voltage* or *current, composite voltage* or *current,* or *ac superimposed on dc.* While a sine wave is shown in Fig. 1-2, the cycle may have any other waveshape, as well. It should be noted, however, that whether the cycle alternates about zero (Fig. 1-1) or about some finite current or voltage (Fig. 1-2), its identity as the basic component of frequency remains the same. It should be noted also that the cycle may not necessarily have the smooth shape shown in Figs. 1-1 and 1-2, but may be distorted. Even when distorted, it is still a cycle, although the distortion may adversely affect the operation of some electronic instruments.



(A) Positive fluctuating. (B) Negative fluctuating.

Fig. 1-2. Typical single fluctuating cycles.

Table 1-1. Values of Frequency Units

1 Hz = 1 cps
1 kHz = 1000 cps = 10^3 Hz
1 MHz = 1,000,000 cps = 10^6 Hz
1 GHz = 1,000,000,000 cps = 10^9 Hz
1 THz = 1,000,000,000,000 cps = 10^{12} Hz

1.2 UNITS OF FREQUENCY

The basic unit of frequency is the *hertz* (abbreviated *Hz*), named in honor of Heinrich Hertz (1857-1894) who first demonstrated radio waves. The hertz is equal to 1 cycle per second:

$$1 \text{ Hz} = 1 \text{ cps} \qquad \text{(Eq 1-1)}$$

Because the hertz is such a small unit for designating high frequencies, larger multiples are used much of the time. These are kilohertz, *kHz* (one thousand hertz); megahertz, *MHz* (one million hertz); gigahertz, *GHz* (one billion hertz); and occasionally terahertz, *THz* (one trillion hertz). Table 1-1 shows the various units of frequency and the corresponding number of cycles per second.

Table 1-2 gives multipliers for easily converting frequency units in Column 1 to frequency units in the other columns. Example: To convert frequency in MHz (Row 3) to frequency in GHz (Column 4), multiply MHz by 0.001. Similarly, to convert to kHz to Hz, multiply kHz by 1000.

Illustrative example: The video carrier of tv Channel 13 has a frequency of 211.25 MHz. What is this frequency (f_c) in kilohertz?

From Table 1-2, the multiplier for MHz to kHz is 1000. Therefore, $f_c = 211.25 \times 1000 = 211{,}250$ kHz.

Table 1-2. Multipliers for Converting Frequency Units

To Convert This to This → ↓	Hz	kHz	MHz	GHz	THz
Hz	1	0.001	1×10^{-6}	1×10^{-9}	1×10^{-12}
kHz	1000	1	0.001	1×10^{-6}	1×10^{-9}
MHz	1×10^{6}	1000	1	0.001	1×10^{-6}
GHz	1×10^{9}	1×10^{6}	1000	1	0.001
THz	1×10^{12}	1×10^{9}	1×10^{6}	1000	1

1.3 FREQUENCY DOMAIN

Encounterable frequencies cover the vast range between 0.00005 Hz (produced by a laboratory-type function generator) to more than 30 million THz (the frequency of some gamma rays). In between lie frequencies in the following categories which include the alternating and oscillating phenomena with which science presently is concerned.[2]

1. *Subaudible frequencies*—Frequencies lower than 20 Hz. They are so called because their effects are below the usual range of human hearing. These frequencies are also termed *subsonic.*
2. *Audio frequencies* (abbreviated *af*)—20 Hz to 10 kHz. This band of frequencies is so called because their effects are audible to the usual human listener. Frequencies higher than 10 kHz accordingly are sometimes called *superaudible* or *supersonic,* and often *ultrasonic frequencies.*
3. *Radio frequencies* (abbreviated rf)—10 kHz to 30,000 MHz. This band comprises the frequencies that make possible radio and the associated processes of television, radar, and remote control. The Federal Communications Commission has subdivided the rf spectrum into the following sections:

   Very-low frequencies (*vlf*)—10 to 30 kHz.
   Low frequencies (*lf*)—30 to 300 kHz.
   Medium frequencies (*mf*)—300 to 3000 kHz.
   High frequencies (*hf*)—
   Very-high frequencies (*vhf*)—30 to 300 MHz.
   Ultrahigh frequencies (*uhf*)—300 to 3000 MHz.
   Superhigh frequencies (*shf*)—3000 to 30,000 MHz.

   Radio frequencies of 1000 MHz (1 GHz) and higher are usually termed *microwave frequencies.* Electronics people have coined several terms to designate special functions, but these latter are not standard categories. One of these is the term *intermediate frequency* (abbreviated *i-f*). A usable intermediate frequency might conceivably come from any part of the wide radio-frequency spectrum. For example, the intermediate frequency used in an a-m broadcast receiver is in the medium-frequency range (455 kHz), the one used in the sound channel of a

[2] Authorities disagree as to the limits of these categories. The figures given here represent a reasonable consensus.

tv receiver (4.5 MHz) or in an fm receiver (10.7 MHz) is in the high-frequency range, and the one used in the first i-f stage of a tv receiver (44 MHz) is in the very-high-frequency range.

4. *Light*—300 GHz to 300,000 THz. The light spectrum lies just above the radio-frequency spectrum and is subdivided as follows:

   Infrared rays (*ir*)—300 to 428,570 GHz.
   Visible light—428,570 to 750,000 GHz.
   Ultraviolet rays (*uv*)—750,000 GHz to 300,000 THz.

5. *X-rays*—300,000 to 30,000,000 THz. X-rays have considerable use in industry, medicine, and science research. They are usually generated by X-ray tubes, but they also arise secondarily from the operation of certain high-voltage electronic equipment, such as some tv receivers, and have been detected in the sun's radiation. Some authorities show an overlap of X-rays and high-frequency ultraviolet rays.

6. *Gamma rays*—3,000,000 THz and above. Note that here there is overlap down into the X-ray range (some authorities assert that gamma rays are the same as X-rays, but mostly of higher frequency). Gamma rays are a byproduct of radioactivity—man-made, as well as natural. Beyond gamma rays lie cosmic rays, but these latter are regarded by some scholars as fast-moving subatomic particles and not rays at all in the sense of oscillating energy.

In conventional electronics, frequency measurements are restricted to a portion of this wide electromagnetic spectrum, the part extending from subaudible frequencies through in-use microwave radio frequencies (roughly 0 to 40 GHz). This means that our first concern is with the frequency of alternating electric currents and voltages and of the fields they set up, and only occasionally with other electromagnetic phenomena, such as light, X-rays, and gamma rays.

1.4 FREQUENCY VS WAVELENGTH

When dealing with electromagnetic waves, it is often preferable to use the wavelength (λ) rather than the frequency of a radiation. Wavelength is the distance measured from crest to crest or from trough to trough over two consecutive cycles of the radiation (see Fig. 1-3). The higher the frequency, the shorter the wavelength, and vice versa. Wavelength is expressed in meters (*m*), centimeters (*cm*), or millimeters

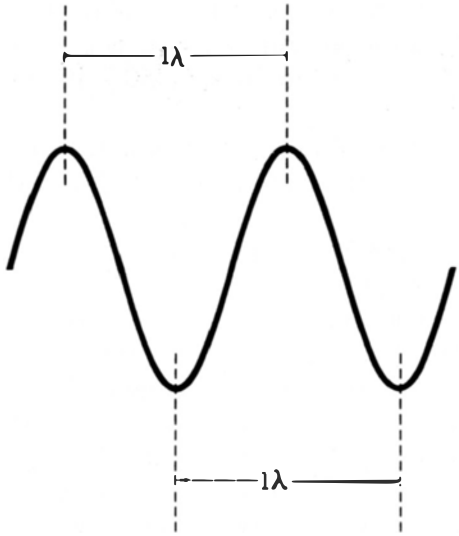


Fig. 1-3. Significance of wavelength.

(*mm*), and may be determined from the frequency in the following manner:

$$\lambda = \frac{300{,}000{,}000}{f} \qquad \text{(Eq 1-2)}$$

where,

300,000,000 (meters per second) is the speed of light,
λ is the wavelength in meters,
f is the frequency in hertz.

Thus, the wavelength of a 100-kHz signal equals 300,000,000 ÷ 100,000 = 3000 m. In some situations, wavelength is more easily measured than frequency; and in such a case, frequency would be calculated from the measured wavelength (see Equation 1-4).

Like frequency, wavelength covers a wide territory. At one extreme, λ for certain X-days may be only 1/100,000 of a millimeter; and at the other extreme (low audio frequencies), the wavelength of 60-Hz power is 5,000,000 meters (3105 miles).

Obviously, if frequency is expressed in units other than hertz, the numerator 300,000,000 must be changed accordingly. General formulas for this purpose are given in Equations 1-3 and 1-4:

$$\lambda = v/f \qquad \text{(Eq 1-3)}$$

where,

λ is the wavelength,
f is the frequency,
v is the velocity of light, or a suitable submultiple.

$$f = v/\lambda \qquad \text{(Eq 1-4)}$$

where,

f is the frequency,
v is the velocity of light, or a suitable submultiple,
λ is the wavelength.

The values of v to be used with selected units of frequency are given in Table 1-3. Thus, for wavelengths in meters and for frequency in kilohertz, v = 300,000; for wavelength in centimeters and for frequency in gigahertz, v = 30; and so on.

Illustrative example: What is the wavelength in meters corresponding to the Citizens band frequency of 27.025 MHz (Channel 6)?

From Table 1-3, for the MHz-to-m conversion, v = 300. Therefore, from Equation 1-3, $\lambda = 300/27.025 = 11.1$ m.

Illustrative example: What is the frequency in kilohertz corresponding to the 75-meter amateur wavelength?

From Table 1-3, for the m-to-kHz conversion, v = 300,000. Therefore, from Equation 1-4, f = 300,000/75 = 4000 kHz.

A complete list of formulas for frequency-to-wavelength and wavelength-to-frequency conversions is given in Appendix B. Multiplier-type conversion factors for changing wavelength and frequency units of one magnitude to those of another magnitude are given in Appendix A.

1.5 PERIOD

At any frequency, the time interval between the beginning and end of one cycle is termed the *period* (symbol, *t*); see Fig. 1-4. The higher the frequency (shorter the wavelength), the

Table 1-3. Value of Numerator (v) in Equations 1-3 and 1-4

Frequency	Wavelength (λ)		
(f)	Meters (m)	Centimeters (cm)	Millimeters (mm)
Hz	3×10^8	3×10^{10}	3×10^{11}
kHz	300,000	3×10^7	3×10^8
MHz	300	30,000	300,000
GHz	0.3	30	300
THz	0.0003	0.03	0.3

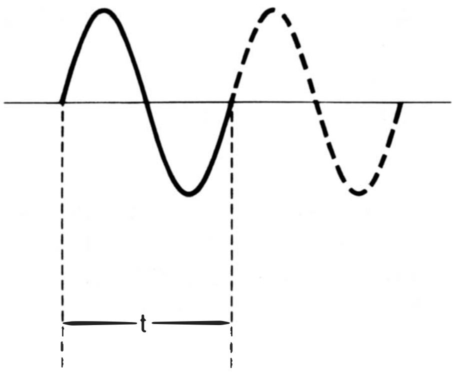


Fig. 1-4. Significance of period.

shorter the period, and vice versa. Period is expressed in seconds (s), milliseconds (ms), or microseconds (μs), and may be determined from frequency in the following manner; $t_{seconds} = 1/f_{hertz}$. Thus, the period of the 60-Hz power-line voltage is $1/60 = 0.0167$ s. Obviously, if frequency is expressed in units other than hertz, the numerator must be changed accordingly. General formulas for this purpose are:

$$t = x/f \qquad \text{(Eq 1-5)}$$

where,

t is the time,
x is the special numerator (see Table 1-4),
f is the frequency.

$$f = x/t \qquad \text{(Eq 1-6)}$$

where,

f is the frequency,
x is the special numerator (see Table 1-4),
t is the time.

The values of x to be used with selected units of frequency are given in Table 1-4. Thus, for frequency in kilohertz and for

Table 1-4. Value of Numerator (x) in Equations 1-5 and 1-6

Frequency (f)	Period (t)		
	Seconds (s)	Milliseconds (ms)	Microseconds (μs)
Hz	1	1000	1×10^{6}
kHz	0.001	1	1000
MHz	1×10^{-6}	0.001	1
GHz	1×10^{-9}	1×10^{-6}	0.001
THz	1×10^{-12}	1×10^{-9}	1×10^{-6}

period in microseconds, x = 1000; for frequency in hertz and for period in milliseconds, x = 1000; and so on.

Illustrative example: What is the period in milliseconds of a 400-Hz current?

From Table 1-4, for the Hz-to-ms calculation, x = 1000. Therefore, from Equation 1-5, t = 1000/400 = 2.5 ms.

Illustrative example: What is the frequency in megahertz corresponding to a period of 5 μs?

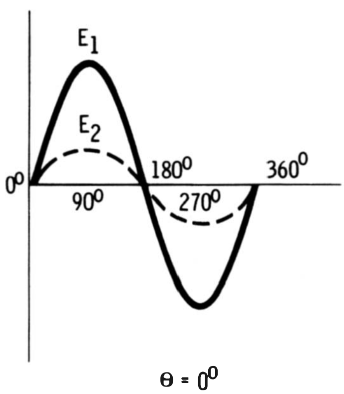
From Table 1-4, for the μs-to-MHz calculation, x = 1. Therefore, from Equation 1-6, f = 1/5 = 0.2 MHz.

A complete list of formulas for frequency-to-period and period-to-frequency conversions is given in Appendix C.

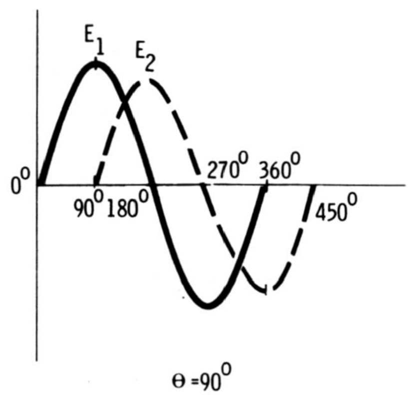
1.6 PHASE

Phase relations sometimes must be taken into consideration in frequency measurements. Two or more varying phenomena (e.g., currents, voltages, waves) are said to be *in phase* when they reach each of their corresponding values at the same instant and in the same direction; they are said to be *out of phase*. (by so many electrical degrees—the angle θ) when they are not so in step with each other. The separate phenomena need not have the same amplitude.

Fig. 1-5A shows two ac voltages which are in phase ($\theta = 0°$); Fig. 1-5B shows two ac voltages which are everywhere 90°



(A) In phase.



(B) Out of phase.

Fig. 1-5. Simple phase relationships.

out of phase with each other ($\theta = 90° = \pi/2$ radians). These components have the same frequency, but E_2 is lower in amplitude than E_1 in this instance. When components differ in frequency, they will be in phase at some points and out of phase at others (when currents are in phase, they add; when they are out of phase, they subtract). Two equal-amplitude components that are of the same frequency but are 180° out of phase at all points completely cancel each other.

In a purely resistive circuit, current and voltage are in phase. In a purely capacitive circuit, current leads voltage by 90°. In a purely inductive circuit, current lags voltage by 90°. In an RC, RL, LC, or LCR circuit, the phase angle and whether the current leads or lags are determined by the magnitudes of resistance and reactance present; whether the latter is capacitive, inductive, or both; and whether the components are in series, parallel, or some combination of the two.

CHAPTER 2

AUDIO-FREQUENCY MEASUREMENT

Frequency measurements in the range 20 Hz to 20 kHz are some of the easiest to make, and numerous instruments and methods are available for the purpose. But, just because some audio frequency measurements are simpler than those of much higher frequencies, one must not presume that care is not needed. Performance and observation both must be painstaking, as in all reliable electrical measurements.

This chapter describes 22 methods of measuring audio frequency. The method selected as best for a particular instance will depend upon suitability, available equipment, and operator experience.

2.1 BEAT-NOTE METHOD

The simplest way to measure an unknown audio frequency is to tune an audio signal generator to zero-beat with it, and then to read the frequency from the generator dial. Either headphones or a meter can serve as the beat indicator. This is known also as the *zero-beat method* or the *search-frequency method.*

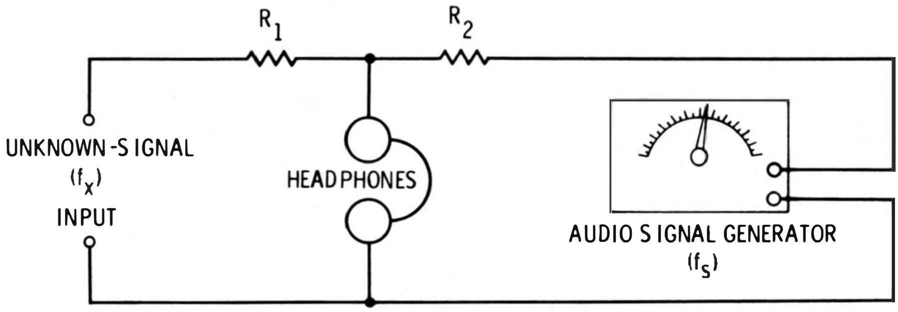
The two signals are applied simultaneously to the indicator. The operator must be careful that the generator is tuned to the actual frequency (f_x) of the signal under test and not to a harmonic or subharmonic of f_x, as each of the latter also will produce beat notes. At the fundamental frequency, the beats are strong, in contrast to those at other frequencies; therefore, tuning the generator to twice the frequency and then to half the frequency and noting the relative strength of the corresponding three beat notes thus will establish the true value of f_x.

If the operator is careful in identifying zero beat and in reading the generator dial, frequency measurements by this method can have an accuracy corresponding to that of the generator, which is ±1% to ±5%, depending upon whether the instrument is laboratory type, service type, factory-built kit, or home-assembled kit.

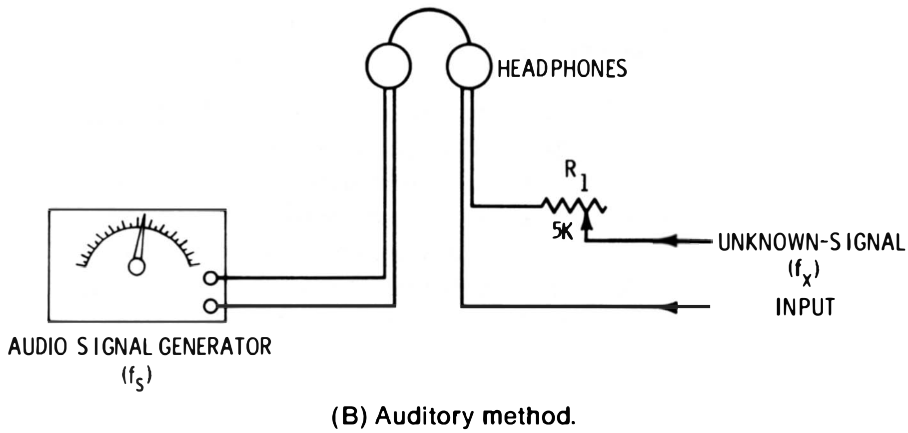
Headphone Method

In Fig. 2-1A, the unknown signal (f_x) and the known, or *standard,* signal (f_s) are applied simultaneously to a pair of high-resistance headphones through identical isolating resistors R_1 and R_2. These resistors may have any convenient stock value between 820 and 1800 ohms each. The headphones may be 2000- or 3000-ohm magnetic type or crystal phones.

Beats will be set up between the two signals when the generator is tuned close to the unknown frequency, and will become



(A) Zero-beat method.



(B) Auditory method.

Fig. 2-1. Headphone methods of measuring audio frequency.

slower as the generator setting comes closer to the unknown frequency. Finally, at zero beat, $f_x = f_s$ and it can be read directly from the generator dial. During the process, the generator output control must be set for best results for an individual listener.

Fig. 2-1B shows an alternate auditory method that can be used when connections can be made separately to each headphone. Here, the unknown signal is applied to one phone through volume control R_1 (a 5000-ohm wirewound potentiometer), and the generator signal is applied to the other phone. Some operators find this method more compatible with their hearing acuity than the first one.

Voltmeter Method

The meter method is silent and has the further advantage of permitting closer recognition of zero beat than is sometimes possible in the auditory method. This arrangement (see Fig. 2-2) employs an electronic ac voltmeter—either a vtvm or tvm.

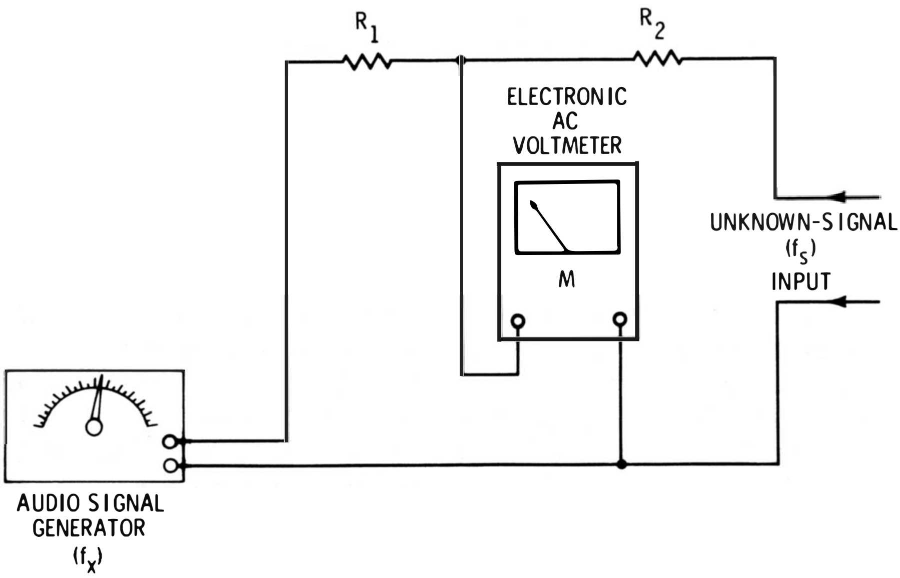


Fig. 2-2. Voltmeter method of measuring audio frequency.

The unknown signal (f_x) and generator signal (f_s) are applied to the meter through identical isolating resistors R_1 and R_2 which can have any stock value between 820 and 1800 ohms each.

First, with the unknown frequency removed, the generator output is adjusted for center-scale deflection of the meter.

Then, when the unknown signal is applied and the generator is tuned, beats take the form of pulsations of the pointer above and below center scale. At zero beat—which can be identified very accurately with this method—the pointer comes to rest, and the frequency can be read from the generator dial. If the generator is tuned either above or below this frequency, the pulsations resume.

For best results, the generator-signal voltage should be higher than that of the unknown-signal voltage. A ratio of 10:1 is good, but not mandatory. This will restrict the pulsations to a narrow section of the scale. The output of either the generator or the unknown-signal source may be adjusted for a manageable beat-note swing of the pointer.

Care must be taken to ignore beat notes resulting from power-line interference leaking through the generator, meter, or test-signal source when either or all are power-line operated. This condition can be detected beforehand by tuning the generator through the power frequency, usually 60 Hz, while watching for beats.

2.2 INDUCTION-TYPE FREQUENCY METER

Fig. 2-3 shows the basic structure of an induction-type frequency meter. This instrument, also known as a *movable-iron-type frequency meter,* gives direct readings in hertz.

In this arrangement, two stationary coils, L_1 and L_2, are mounted at right angles to each other. The movable element is a long, narrow soft-iron vane (V) with an attached pointer. The deflection of this vane is proportional to the resultant magnetic field set up by L_1 and L_2. The resistance-inductance network connected to the coils reduces the phase difference between currents flowing in these coils and thereby prevents the iron vane from rotating instead of deflecting. Rotation of the magnetic field is now no longer uniform, but irregular; and the vane, because of its inertia, cannot follow this field, so it assumes a position proportional to the frequency of the current.

This type of instrument is usually supplied for power-line frequencies—25, 40, 50, 60, and 125 Hz—however, such meters have been manufactured for frequencies as high as 500 Hz. The normal operating frequency for which the meter is intended appears at center scale, with an equal number of hertz inscribed above and below that frequency (depending upon center frequency, there is usually a 30% to 85% frequency variation above and below center scale). Depending upon make and model, frequency accuracy can be as good as 0.5%.

Induction-type frequency meters are supplied for single-frequency/single-voltage, single-frequency/double-voltage, or double-frequency/double-voltage operation. Typical accuracy is 0.5% of indicated frequency. Typical operating-voltage ranges are 100 to 125 V and 125 to 150 V. A potential transformer must be used at higher voltages, such as 220 to 250 V

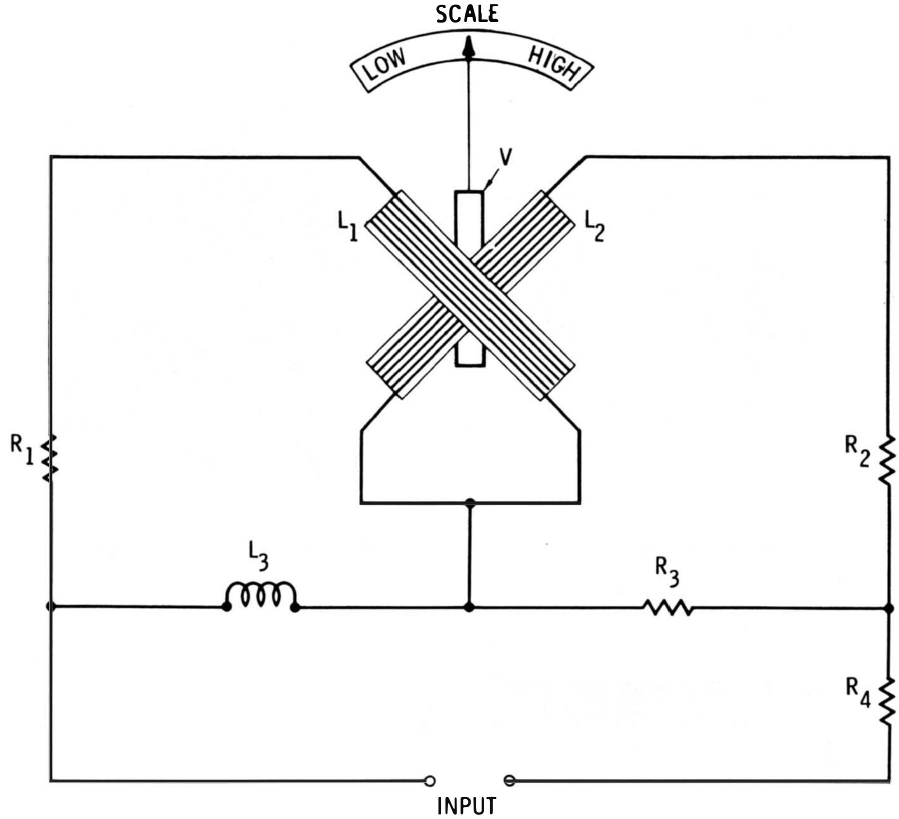


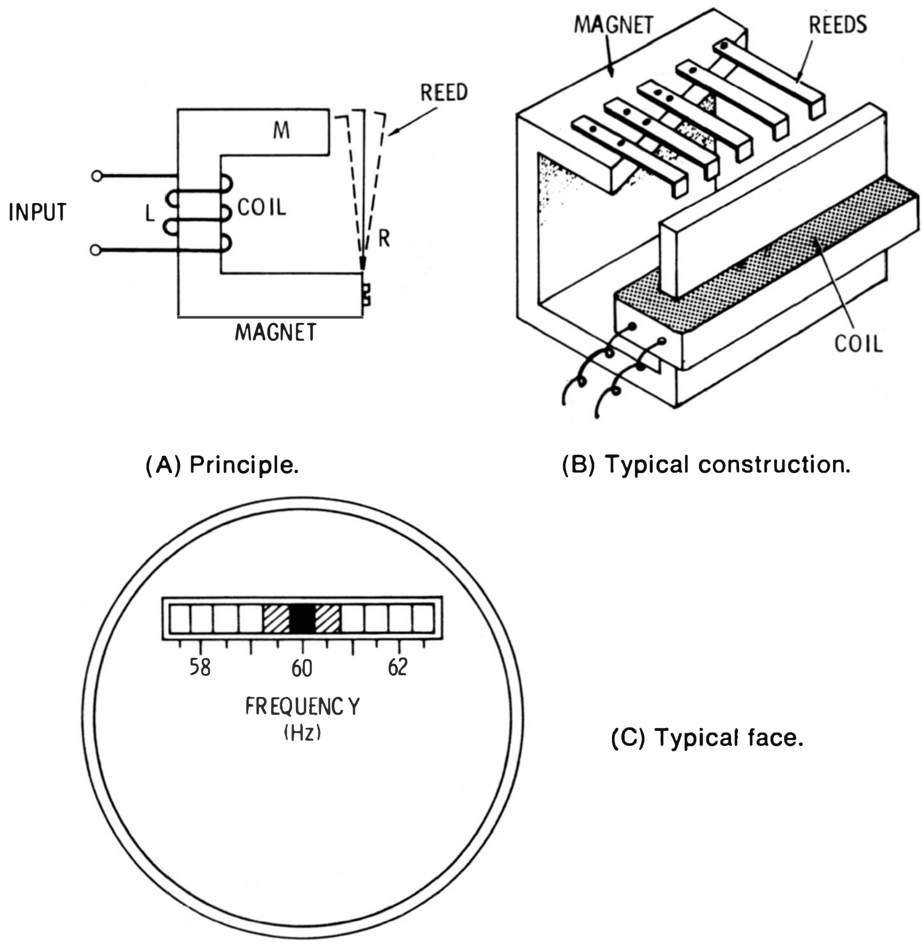
Fig. 2-3. Induction-type frequency meter.

and 250 to 300 V. The operating power of the instrument must be taken into consideration in many applications of this type of instrument; a typical value is 2.5 watts for a small 60-Hz meter. These voltage and power demands restrict the induction-type frequency meter to large-signal applications.

2.3 REED-TYPE FREQUENCY METER

This instrument is also known as the *vibrating-reed meter* or *Frahm-type meter*. Its operating principle is illustrated by Fig. 2-4A. In this arrangement, M is a permanent magnet. On the yoke of this magnet is wound a coil (L) consisting of many turns of fine wire. This coil is connected to the source of audio-frequency current of unknown frequency.

Reed R (a thin strip of magnetic metal, such as iron or steel) is fastened at its lower end to one pole of the magnet; the upper end of this reed stands a short distance from the face of the other pole of the magnet. This springy reed has a natural period of vibration which is determined chiefly by its length and thickness.



(A) Principle.

(B) Typical construction.

(C) Typical face.

Fig. 2-4. Reed-type frequency meter.

When an alternating current flows through the coil, the strength of the resulting magnetic field alternates at the ac frequency and sets the reed into vibration. The vibration is most vigorous when the frequency of the current equals the natural vibration frequency of the reed. In fact, the vibration is then so intense that the free end of the reed becomes invisible. When the frequency of the current is a few hertz above or below the reed frequency, the reed vibrates, but not so intensely as it does at its natural frequency because of the relatively low Q of the reed.

In the actual meter, several reeds, cut to various proper lengths, are mounted side by side on one pole-piece of the magnet, as shown in Fig. 2-4B. The top of the pole is slanted so that, although the reeds are of unequal length, their free ends are in line for easy viewing from the front. The tips, bent into small flags, are painted white for good visibility. If the reed lengths differ only slightly, several adjacent reeds (usually three) will vibrate at a given frequency, but the one whose natural vibration corresponds to the frequency is the most active and may readily be identified. Generally, this one will disappear from sight, while immediately adjacent ones will appear blurred. This action is illustrated in Fig. 2-4C which shows the face of a reed-type meter. Here, the 60-Hz reed has disappeared, while the 59.5-Hz and 60.5-Hz reeds vibrate less vigorously and appear blurred. The manufacturer can tune the reeds very accurately by precisely controlling their length or by appropriately mounting them along the slanted pole piece.

Typical accuracy is 0.3% of indicated frequency. Operating voltages range from 5 V to 660 V rms. Depending upon make and model, the power consumed by the meter ranges from 0.75 W to 2 W. The response of the meter is reasonably free from the effects of voltage change, temperature change, and waveform.

A 57.5-60-62.5-Hz scale is shown in Fig. 2-4C. Other common scales extend from 40-45-50 Hz to 380-400-420 Hz. The total number of reeds ranges from 5 to 21. Some meters have more than one frequency scale.

2.4 ANALOG-TYPE ELECTRONIC FREQUENCY METER

An analog-type electronic frequency meter unlike the instruments described in Sections 2.2 and 2.3, provides high input impedance (therefore, virtually no drain is imposed upon the signal source) and wide range (typically, 0 to 100 kHz in four bands: 0 to 100 Hz, 0 to 1 kHz, 0 to 10 kHz, and 0 to 100 kHz). This instrument is available in tube or transistor version. Fig. 2-5 shows a circuit employing two field-effect transistors (FET).

The frequency is indicated on the scale specially drawn for the 0- to 50-dc microammeter (M). The frequency is independent of signal amplitude from 1.7-V rms upward and is independent of waveform over a wide range. The response is linear; hence, only one point need be calibrated in each frequency band.

The arrangement consists essentially of two overdriven amplifiers. The output of the last stage (Q_2) accordingly is a square wave which is applied to an RC circuit (R_6 through R_9 and C_4 through C_7) and rectifier diodes D_1 and D_2. Since the square wave is of constant amplitude, the deflection of the meter (M) depends only on the *number* of current pulses per second, and therefore is directly proportional to the signal frequency.

The instrument must be initially calibrated at one point in each frequency band, and this need be done only once (the best point is the top frequency—full-scale deflection of the meter (M) in each band). Rheostats R_6, R_7, R_8, and R_9 are the CALIBRATION controls and are usually provided with slotted shafts for screwdriver adjustment. They are mounted inside the instrument case, for protection against tampering.

Calibration Procedure:

1. Close switch S_1.
2. Set RANGE switch S_2-S_3 to position A.
3. Connect an accurate audio signal generator to the SIGNAL INPUT terminals.
4. Set the signal frequency to 100 Hz and adjust R_6 for full-scale deflection of meter, M.
5. Set S_2-S_3 to position B.
6. Set the signal frequency to 1 kHz and adjust R_7 for full-scale deflection of the meter.
7. Set S_2-S_3 to position C.
8. Set the signal frequency to 10 kHz and adjust R_8 for full-scale deflection of the meter.
9. Set S_2-S_3 to position D.
10. Set the signal frequency to 100 kHz and adjust R_9 for full-scale deflection of the meter.

If the instrument is carefully calibrated according to foregoing procedure, its accuracy at the calibration-frequency points should equal that of the generator. If the dc response of the microammeter is linear, other frequencies in each band should fall on the corresponding scale division. Individual points along the meter scale can, of course, be checked with a variable-frequency generator.

A wide-range factory-built instrument—Hewlett-Packard 5210A—provides coverage from 3 Hz to 10 MHz in 6 ranges: 0 to 100 Hz, 0 to 1 kHz, 0 to 10 kHz, 0 to 100 kHz, 0 to 1 MHz, and 0 to 10 MHz. Its accuracy is 1% of the reading from 10% of full scale up.

At this writing, the analog-type instrument has been superseded almost entirely by the digital type (see Section 2.5). However, it survives in the model just discussed and as a frequency indicator in some signal generators. The kit-type meter has disappeared, but the homemade version (Fig. 2-5) is to be recommended to private builders who need a reliable, easily calibrated audio-frequency meter which can be assembled quickly at a fraction of the cost of a digital instrument.

2.5 DIGITAL-TYPE ELECTRONIC FREQUENCY METER

Like the analog-type instrument described in Section 2.4, the digital-type frequency meter is electronic and provides high input impedance and wide range. Going a step further, however, the digital instrument dispenses with the indicating meter and displays the frequency as a set of digits presented by electronic readout devices. Thus, the digital instrument is fully electronic.

The digital-type instrument consists essentially of an electronic counter circuit, which is automatically gated to total the number of cycles of pulses of an applied signal that arrive in 1 second, and which operates a 5- or 8-digit display (more digits in some models) to show this count. The 1-second *sampling-time* gate is controlled by an accurate timing signal ("clock") that is internally generated, usually by a temperature-controlled crystal oscillator. Some models also provide selectable gating intervals from 0.1 μs to 10 s.

There are numerous variations of this scheme. Fig. 2-6 shows the block diagram of one version. In this arrangement, the signal of unknown frequency is presented to a *signal-processor* (A) which provides amplification and high input impedance and shapes the signal properly (converts it into a square wave) for triggering the *counter* (D). The time-base generator (C) delivers a square wave of correct amplitude, period, and polarity to hold the *gate* (B) open for the desired interval, say 1 second. Pulses passing through the gate actuate the counter which indicates on the *display* (E) the total number of pulses that passed through the gate during the time interval. A pulse from the time-base generator then actuates the *reset* circuit (F) which, in turn, generates a pulse that resets the counter to zero. The entire sequence then is repeated. The display indicates the frequency and, in addition, automatically places the decimal point.

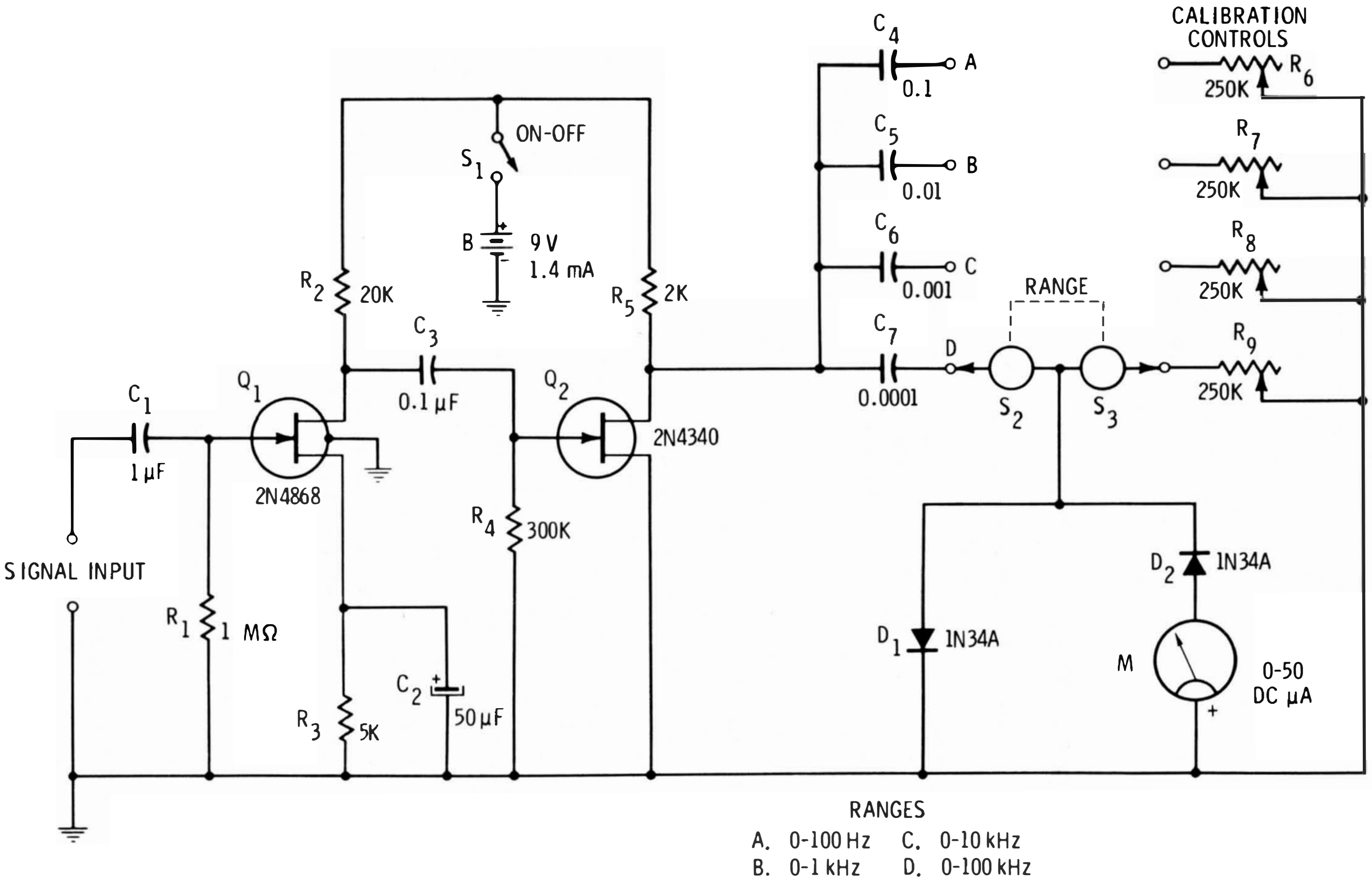


Fig. 2-5. Analog-type electronic frequency meter.

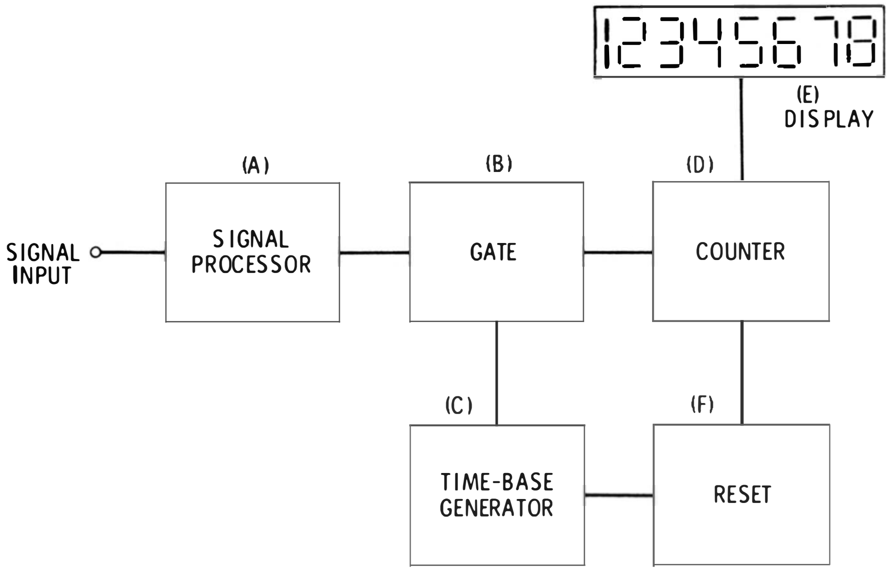


Fig. 2-6. Digital-type electronic frequency meter.

Commercially available digital instruments have a wide operating range (e.g., 0 to 50 MHz) ; they are useful, therefore, far beyond the audio frequencies. Typical accuracy is ±1 digit ± the time-base stability. Depending upon make and model, sensitivity at audio frequencies is 5 mV to 100 mV rms sine wave, and input impedance is 1 megohm (shunted by 15 pF to 35 pF). These instruments are available in factory-built and kit versions.

2.6 OSCILLOSCOPE METHODS

The cathode-ray oscilloscope is useful in a number of ways in the measurement of audio frequencies. The principal ways are described below. In each of these, the oscilloscope serves as a reliable indicator of the relationship between an unknown frequency and a standard frequency. In all except Method A, the standard frequency is supplied by a separate device. When the measurements are carefully made, the accuracy of these methods can equal that of the standard-frequency source.

A. Oscilloscope Having Calibrated Time Base

Many modern oscilloscopes have a calibrated horizontal sweep which allows time intervals to be read along the horizontal axis of the screen. The front-panel sweep-rate control accordingly is graduated in time units per scale division. In a laboratory-type instrument (e.g., Hewlett-Packard Model 1722A), the rates typically are 10 ns/div to 50 ns/div, 100 ns/div to 20 ms/div, and 50 ms/div to 0.5 s/div, and these are provided with X1 and X10 multipliers. (In the cited instrument, the 10-ns and 50-ms ranges have an accuracy of ±3%, and the 100-ns range has an accuracy of ±2%.)

To check the frequency of an unknown signal applied to the VERTICAL INPUT terminals of the oscilloscope, adjust the sweep rate to give one stationary cycle on the screen. Then, measure the width of this cycle in scale divisions and determine the corresponding time interval from the settings of the sweep control and multiplier. This gives the period (t) of the signal (See Section 1.5, Chapter 1, for a discussion of period). Finally, calculate the frequency: $f_x = 1/t$, where f_x is in hertz and t is in seconds. For frequencies other than hertz and for periods other than seconds, use the appropriate formulas given in Appendix C.

Illustrative example: The width of a single cycle on the oscilloscope screen is found to be 3.5 divisions. The sweep control is set at 5 ms/div, and the multiplier is set to $\times 1$.

Here, the period $t = 3.5 \times 5 = 17.5$ ms $= 0.0175$ s; therefore, $f = 1/0.0175 = 57.1$ Hz.

Calibrated time bases are not restricted to expensive, laboratory-type instruments. A kit-type oscilloscope can also offer this convenience. The Heathkit IO-105 instrument, for example, has 18 calibrated rates from 0.2 μs/cm to 100 ms/cm at ±3% accuracy, in a 1, 2, 5 sequence.

B. Use of Lissajous Figures

These distinctive patterns (named for their discoverer, Jules A. Lissajous, 1822–1880) permit use of the oscilloscope to check unknown frequency against a standard frequency even if one is a harmonic of the other. The patterns shown here are obtained with two sine-wave signals. Somewhat similar, though distorted, patterns result when one or both signals are nonsinusoidal.

Fig. 2-7 shows the test setup for Lissajous figures. The standard-signal source usually is a well-calibrated variable-frequency audio generator which is used to search out the unknown frequency. The internal sweep of the oscilloscope is switched off. With this arrangement, a stationary pattern

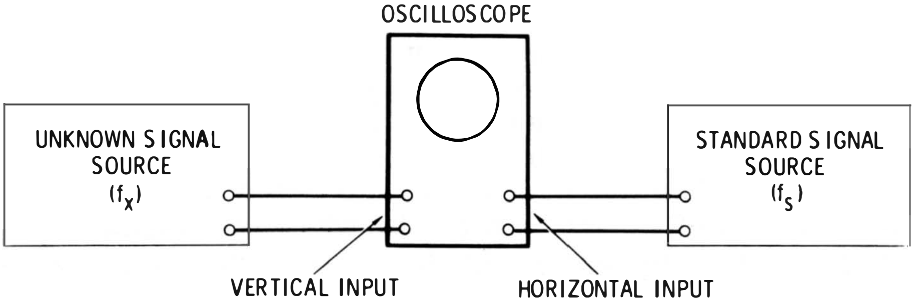
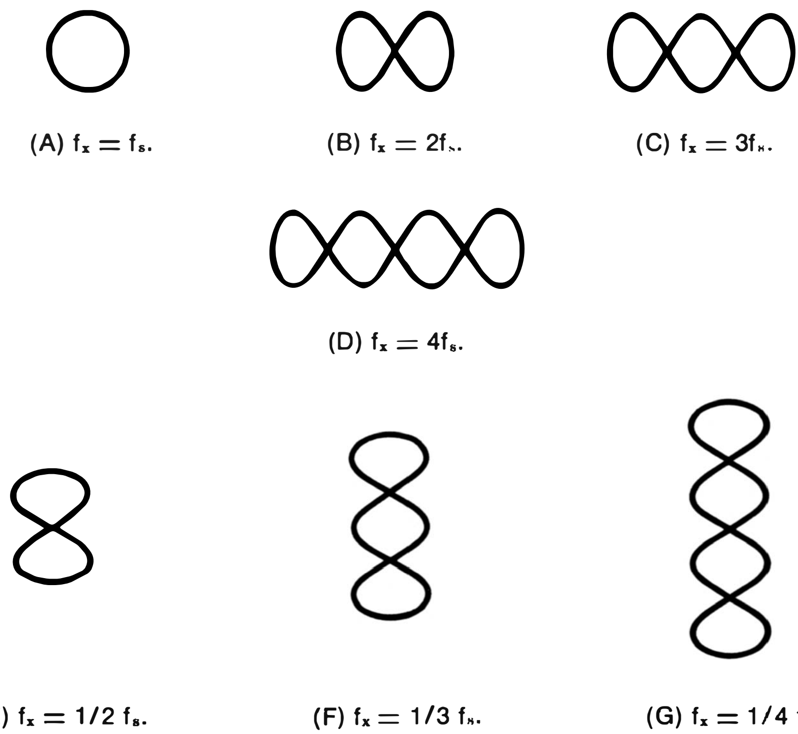


Fig. 2-7. Test setup for Lissajous figures.

appears on the screen when the unknown frequency (f_x) is equal to the standard frequency (f_s) or is an exact multiple (n) or submultiple (1/n) of f_s. When f_x is not equal to f_s, nf_s, or $1/nf_s$, the pattern will spin about its axis—in one direction when f_x is lower, in the opposite direction when f_x is higher.

Fig. 2-8 shows patterns for several common frequency ratios when the phase angle between the two signals is 90°. When the unknown frequency equals the standard frequency, a stationary circle results (Fig. 2-8A) ; when the unknown frequency is twice the standard frequency, the stationary pattern has two horizontal loops (Fig. 2-8B) ; and so on. In each instance, the



(A) $f_x = f_s$. (B) $f_x = 2f_s$. (C) $f_x = 3f_s$.

(D) $f_x = 4f_s$.

(E) $f_x = 1/2\ f_s$. (F) $f_x = 1/3\ f_s$. (G) $f_x = 1/4\ f_s$.

Fig. 2-8. Typical Lissajous figures.

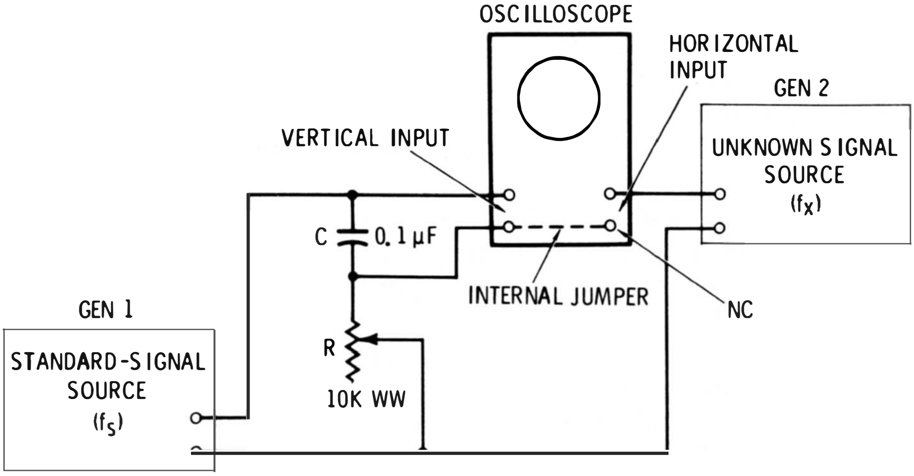
number of loops is counted to give the value of the multiplier n by which standard frequency f_s must be multiplied (the circle in Fig. 2-8A is one loop, so here $f_x = 1f_s = f_s$). When the unknown frequency is a submultiple of the known frequency, the loops in the stationary pattern are stacked vertically, as in Fig. 2-8E to 2-8G. Here, the number of loops is counted to give the denominator n of the fraction $1/n$ by which the standard frequency, f_s, must be multiplied, Thus, three loops (Fig. 2-8F) give the fraction 1/3, and $f_x = 1/3\ f_s$.

Only a few of the possible patterns are shown in Fig. 2-8. From this description, however, it should be clear that the procedure can be extended to include the highest frequency ratio whose corresponding number of loops can be accurately counted on a particular screen. The limit is dictated ultimately by the screen size, resolution and stability of the oscilloscope and by the keenness of the operator's eyesight. When the ratio is so high that it makes an accurate count doubtful, one of the following methods described in Parts C, D, or E may be preferred.

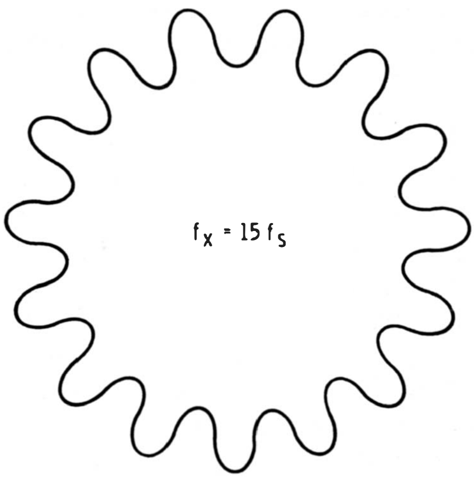
C. Use of Gear-Wheel Pattern

This method (see test setup in Fig. 2-9A) traces a single stationary circle (representing standard frequency f_s) with a circumference that is wrinkled by sine-wave cycles which indicate the number of times f_s must be multiplied to give the unknown frequency, f_x. The signal from GEN 2 modulates that from GEN 1, thereby producing the characteristic "gear-wheel" pattern. Fig. 2-9B shows a typical pattern—in this case having 15 cycles or "teeth" to show that $f_x = 15f_s$. The wheel is stationary when f_x is an exact multiple (n) of f_s, but spins when f_x is lower or higher than f_s.

The underlying circular trace is produced by a resistance-capacitance phase-shift network, RC, operated from the standard-frequency generator, GEN 1. With the 0.1-μF capacitor and the 10,000-ohm wirewound rheostat shown in Fig. 2-9A, the network may be adjusted (together with the vertical and horizontal gain controls of the oscilloscope) for an acceptable circle, at any frequency between 20 Hz and 20 kHz. When the trace is an ellipse, the cycles at the small ends of the pattern are distorted and crowded; nevertheless, they can be counted unless they are too compressed horizontally to be separated. The unknown-signal source, GEN 2, should have low or medium output impedance and should provide an internal conductive path between its output terminals. If such a path is not present, as when the generator has capacitance-coupled output, a transformer must be connected between GEN 2 and the oscilloscope.



(A) Test setup.



(B) Pattern.

Fig. 2-9. Arrangement for gear-wheel pattern.

The transformer characteristics are unimportant, so long as a sufficient voltage is supplied to the horizontal channel of the oscilloscope.

Procedure:

1. Set up the equipment as shown in Fig. 2-9A.
2. With the oscilloscope and GEN 1 switched ON and with GEN 2 OFF, set the oscilloscope SWEEP and SYNC to EXTERNAL.
3. Adjust rheostat R and the VERTICAL and HORIZONTAL GAIN controls of the oscilloscope for a good circle pattern.
4. Switch-on GEN 2, noting that "teeth" appear on the circumference of the circle.

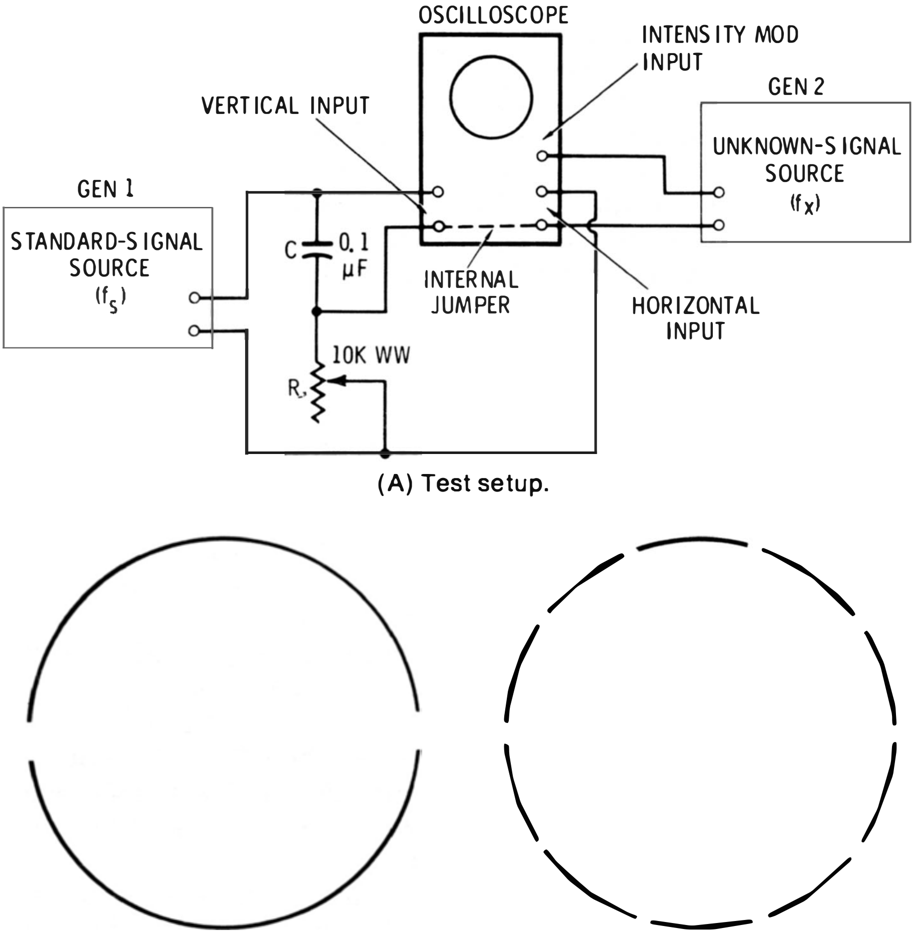
5. Adjust unknown frequency f_x of GEN 2 until the wheel stands still, and adjust the output of GEN 2 for teeth small enough that they do not distort the circle.
6. Count the teeth and multiply standard frequency f_s by that number to obtain the value of known frequency f_x.

This method is extremely useful when GEN 1 is a single-frequency device and GEN 2 is a variable-frequency one. Under these conditions, the variable-frequency unit may be tuned to, and calibrated at, a large number of points limited only by the operator's ability to find and count the teeth. Thus, a variable-frequency audio generator can be calibrated at numerous harmonics of the 60-Hz power-line frequency. The unknown frequency may be determined with the same accuracy as that of the standard generator. An obvious disadvantage of the circuit is the floating oscilloscope. In most setups, however, this seems to introduce no hum-interference problems; but, at high frequencies, the lead length, lead dress, and equipment placement will be important.

D. Use of Segmented Circle

This method (see test setup in Fig. 2-10A) traces a single stationary circle (representing standard frequency f_s) whose circumference is broken up into a number of segments indicating the number of times f_s must be multiplied to give the unknown frequency, f_x. The signal from GEN 2, the unknown-signal source, is applied to the z-axis (intensity-modulation) input of the oscilloscope, and it modulates the circular trace to give the characteristic segmented-circle pattern. Fig. 2-10B shows the resulting pattern with two segments, indicating that $f_x = 2f_s$; Fig. 2-10C shows the pattern with 10 segments, indicating that $f_x = 10f_s$. The circle is stationary when f_x is an exact multiple (n) of f_s, but spins when f_x is higher or lower than nf_s.

As in the gear-wheel method described under Part C, the underlying circle trace is produced here by a resistance-capacitance phase-shift network (RC) operated from the standard-frequency generator, GEN 1. With the 0.1-μF capacitor and the 10,000-ohm wirewound rheostat shown in Fig. 2-10A, the network may be adjusted (together with the HORIZONTAL and VERTICAL GAIN controls of the oscilloscope) for an acceptable circular trace at any frequency between 20 Hz and 20 kHz. When the trace is an ellipse, the segments at the small ends of the ellipse are shorter than the others; nevertheless, they can be recognized and easily counted if they are not severely crowded.



(A) Test setup.

(B) Pattern for $f_x = 2f_s$.

(C) Pattern for $f_x = 10f_s$.

Fig. 2-10. Arrangement for segmented-circle pattern.

Procedure:

1. Set up the equipment as shown in Fig. 2-10A.
2. With the oscilloscope and GEN 1 switched ON and GEN 2 OFF, set the oscilloscope SWEEP and SYNC to EXTERNAL.
3. Adjust rheostat R and the VERTICAL and HORIZONTAL GAIN controls of the oscilloscope for a circle pattern.
4. Switch-on GEN 2, noting that the circumference of the circle breaks up into segments.
5. Adjust the frequency of GEN 1 or GEN 2, whichever is variable, until the circle stands still, and adjust the INTENSITY control of the oscilloscope for the best visibility of the segments.
6. Count the segments and multiply standard frequency f_s by this number to find the value of unknown frequency f_x.

Like the gear wheel, the segmented circle is extremely useful when GEN 1 is a single-frequency device and GEN 2 a variable-frequency one. Under these conditions, the variable-frequency unit may be tuned to, and calibrated at, a large number of points limited only by the resolution of the oscilloscope and the operator's ability to separate and count the segments. Thus, a variable-frequency audio oscillator can be calibrated at numerous harmonics of the 60-Hz power-line frequency. The unknown frequency may be determined with the same accuracy as that of the standard generator.

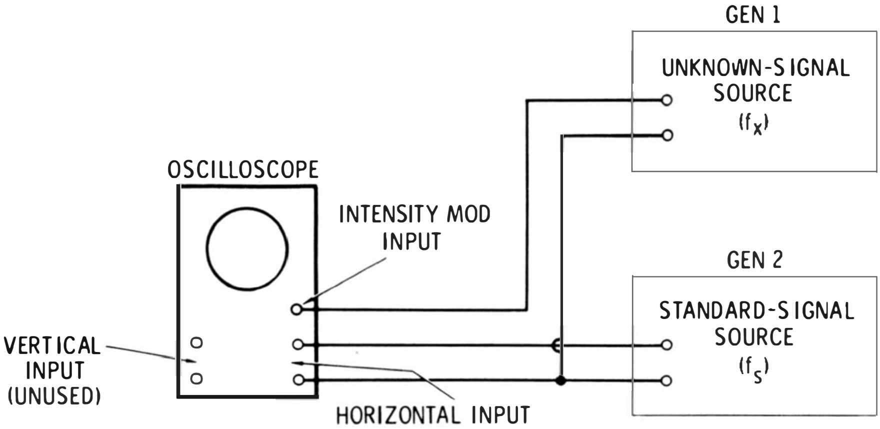
E. Use of Broken Line

This method (see test setup in Fig. 2-11A) traces a single horizontal line (representing standard frequency f_s) which is broken up into a number of segments indicating the number of times f_s must be multiplied to give the unknown frequency, f_x. The signal from the unknown-signal source, GEN 1, is applied to the Z-axis (intensity-modulation) input of the oscilloscope and modulates the horizontal-line trace, thereby producing the characteristic broken-line pattern. Fig. 2-11B shows the resulting pattern with two segments when $f_x = 2f_s$; Fig. 2-11C shows the pattern with five segments when $f_x = 5f_s$. The end segments often appear as dots. The pattern is stationary when f_x is an exact multiple (n) of f_s, but the segments crawl horizontally when f_x is lower or higher than nf_s.

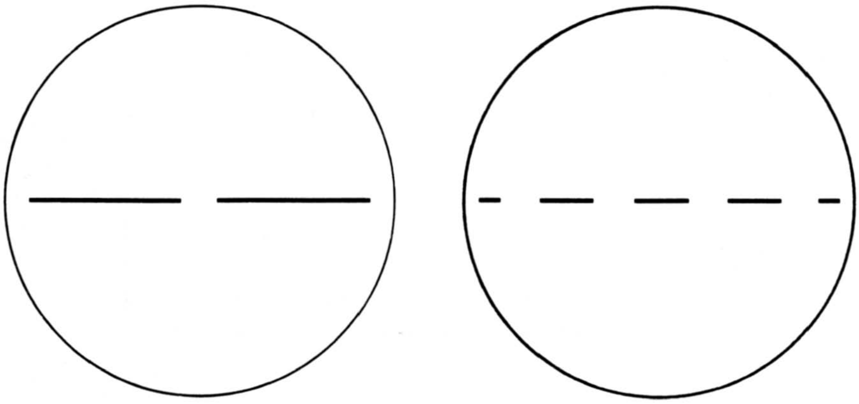
The underlying horizontal-line trace is produced by the standard-signal source, GEN 2, which is connected to the HORIZONTAL input of the oscilloscope. The VERTICAL input is not used, and the internal SWEEP and SYNC are switched OFF. The sine-wave output of GEN 2 thus sweeps the spot back and forth to generate the horizontal line whose width is adjustable with the HORIZONTAL GAIN control.

Procedure:

1. Set up the equipment as shown in Fig. 2-11A.
2. With the oscilloscope and GEN 2 switched ON and with GEN 1 OFF, set the oscilloscope SWEEP and SYNC to EXTERNAL, and set the VERTICAL GAIN control to zero.
3. Note that the standard signal produces a horizontal-line trace. Adjust the HORIZONTAL GAIN control to spread the line over a good portion of the screen (for example, 4 inches on a 5-inch screen).
4. Switch-on GEN 1, noting that the line breaks up into segments.



(A) Test setup.



(B) Pattern for $f_x = 2f_s$. (C) Pattern for $f_x = 5f_s$.

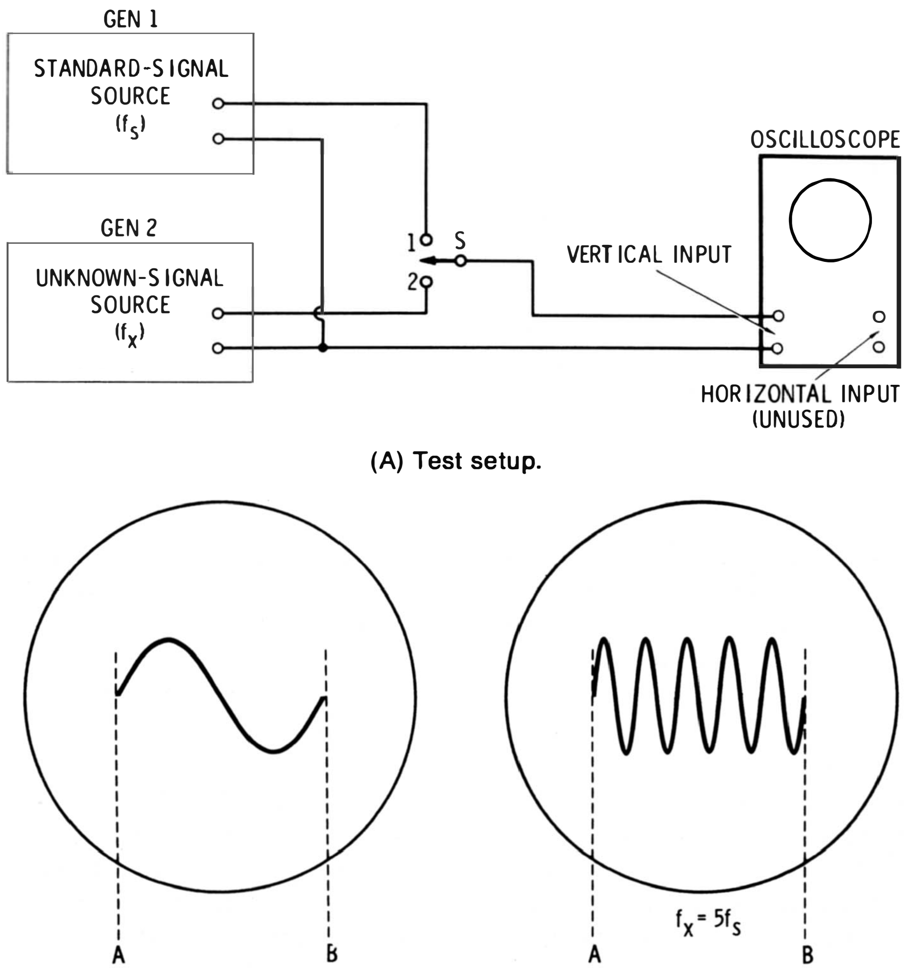
Fig. 2-11. Arrangement for broken-line pattern.

5. Adjust unknown frequency f_x of GEN 1 until the segments stand still, and adjust the INTENSITY control of the oscilloscope for the best visibility of the segments.
6. Count the segments and multiply standard frequency f_s by that number to find the value of unknown frequency f_x.

Like the gear wheel and the segmented circle described earlier, the broken line is extremely useful when GEN 2 is a single-frequency device and GEN 1 a variable-frequency one. Under these conditions, the variable-frequency unit may be tuned to, and calibrated at, a large number of points limited only by the resolution of the oscilloscope and the operator's ability to separate and count the segments. Thus, a variable-frequency audio oscillator can be calibrated at numerous harmonics of the 60-Hz power-line frequency. The unknown frequency may be determined with the same accuracy as that of the standard generator.

F. Use of Individually Calibrated Screen

In this method (see test setup in Fig. 2-12A), the oscilloscope screen is first frequency-calibrated by obtaining as a pattern a single stationary cycle of an accurately known standard frequency (f_s) spread over a chosen screen width. Then, f_s is removed, the unknown frequency (f_x) is substituted, and the number (n) of cycles that occupy the same screen width are counted. Unknown frequency f_x then is determined by multiplying f_s by n. For illustration, Fig. 2-12B shows the single standard-frequency cycle spread horizontally between points A and B on the screen, and Fig. 2-12C shows the substituted



(A) Test setup.

(B) Set pattern.

(C) Measure pattern.

Fig. 2-12. Arrangement for individually calibrated screen.

unknown frequency, f_x, which gives five cycles in the same width AB. Here, $f_x = 5f_s$. The internal SWEEP and SYNC of the oscilloscope must be very stable.

In Fig. 2-12A, when switch S is at its position 1, the standard-signal source (GEN 1) is connected to the VERTICAL INPUT terminals of the oscilloscope; when S is at position 2, GEN 1 is disconnected and the unknown-signal source (GEN 2) is connected to the VERTICAL INPUT terminals.

Procedure:

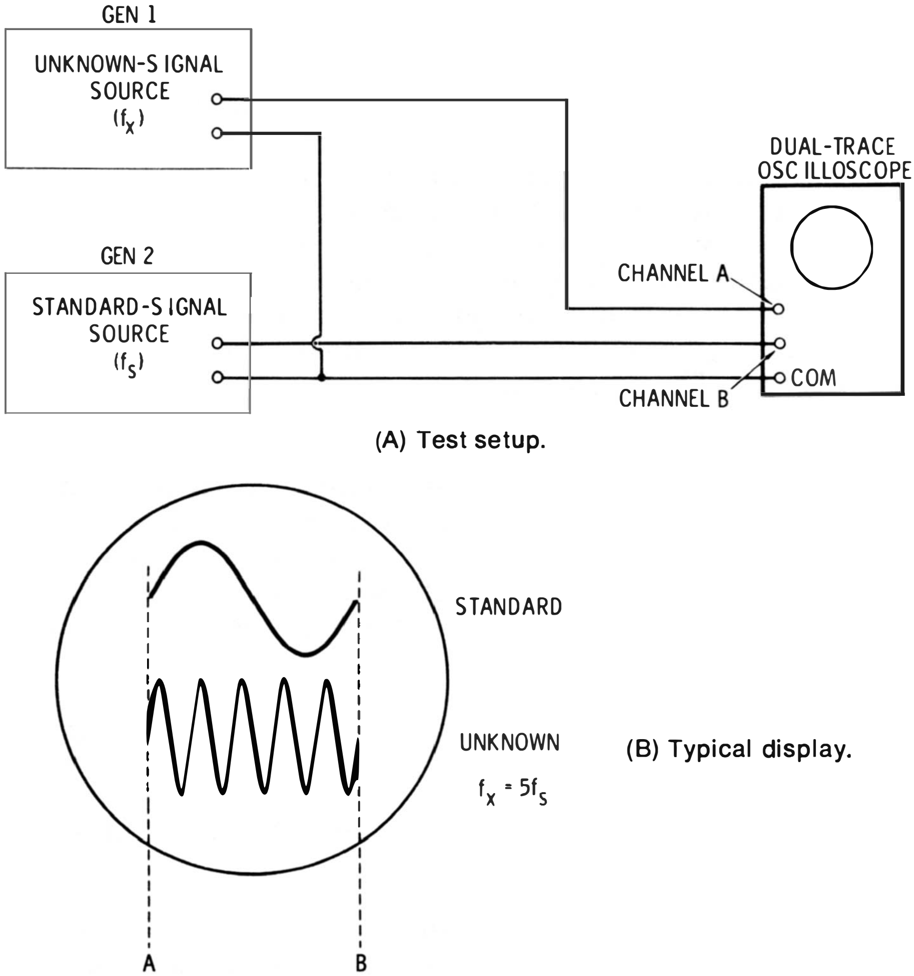
1. Set up the equipment as shown in Fig. 2-12A.
2. Throw switch S to position 1.
3. With the oscilloscope SYNC and SWEEP set to INTERNAL, adjust the SWEEP and SYNC for a single stationary cycle of standard frequency f_s.
4. Set the HORIZONTAL GAIN control of the oscilloscope to spread the cycle over the desired number of horizontal divisions on the screen, and set the VERTICAL GAIN control for the desired height of the pattern.
5. Without disturbing any controls of the oscilloscope, throw switch S to position 2, noting the increased number (n) of stationary cycles now appearing in the same screen width as that previously occupied by the single calibration cycle.
6. Count the number of cycles and calculate unknown frequency f_x by multiplying the standard frequency by that number. Thus, $f_x = nf_s$.

With a stable oscilloscope, this method will afford an accuracy equal to that of the standard-signal source, and may be used to measure frequencies equal to or much higher than the standard frequency. The highest frequency that can be measured depends upon the reliability with which narrow cycles of the unknown frequency can be distinguished on the screen and counted. With a 5-inch oscilloscope, it is advisable to use only 4 inches of the screen and to keep the cycles no narrower than $\frac{1}{16}$ inch each. This allows 64 cycles (corresponding to a multiplier $n = 64$) in the 4-inch space. With a 60-Hz standard frequency, the highest measurable frequency then would be 3840 Hz; with $f_s = 1000$ Hz, f_x maximum would be 64 kHz; and so on.

G. Use of Dual-Trace Oscilloscope

This method is similar to Method F but requires no manual switch. A dual-trace or dual-beam oscilloscope is used with the same internal linear sweep applied simultaneously to both channels. One channel displays one cycle of the standard frequency, and the other channel displays cycles of the unknown frequency in the same screen width, the two displays appearing simultaneously. Fig. 2-13A shows the test setup, and Fig. 2-13B the type of display that is obtained.

The SWEEP and SYNC controls of the oscilloscope are adjusted for a single stationary cycle of the standard frequency (f_s), and the HORIZONTAL GAIN control is adjusted to spread this cycle over a desired screen width (A to B to Fig. 2-13B). Cycles of the unknown frequency (f_s) appear simultaneously below the standard-frequency cycle. The number (n) of cycles in the unknown-frequency pattern is counted, and the unknown frequency, f_x, then is determined by multiplying standard frequency f_s by that number. For illustration, Fig. 2-13B shows



(A) Test setup.

(B) Typical display.

Fig. 2-13. Arrangement for dual-trace oscilloscope.

the single standard-frequency cycle spread between points A and B on the screen, and above this cycle, five cycles of the unknown frequency appear simultaneously between A and B. Here, $f_x = 5f_s$.

With a stable oscilloscope, this method—like the preceding one—will afford an accuracy equal to that of the standard-signal source and may be used to measure frequencies equal to or much higher than the standard frequency. Since it requires no manual switching between the two signal sources, this method is reasonably fast. The highest frequency that can be measured depends upon the reliability with which narrow cycles of the unknown signal can be separated on the screen and counted. With a 5-inch oscilloscope, it is advisable to use only four inches of the screen and to keep the f_x cycles no narrower than $\frac{1}{16}$ inch each. This allows 64 cycles in the 4-inch space. With a 60-Hz standard frequency, the highest measurable frequency then would be 3840 Hz; with $f_s = 1000$ Hz, f_x maximum would be 64 kHz; and so on.

2.7 TUNABLE INSTRUMENTS

Several continuously variable instruments may be tuned to any frequency in the audio spectrum in much the same way that a receiver is tuned to radio frequencies, and the audio frequency is read directly from the tuning dial. These devices include the *wave analyzer, tuned null detector, tuned sound and vibration analyzer,* and *distortion meter.* Essentially, all are sharp-tuning electronic ac voltmeters. While each of these instruments is intended primarily for other applications, they are useful also for audio-frequency measurement.

A. Wave analyzer

There are two types: *heterodyne* and *RC-tuned.* The heterodyne type employs a circuit somewhat similar to a superheterodyne radio receiver, the unknown audio frequency being converted to a 50- or 100-kHz intermediate frequency by a local rf oscillator and balanced modulator and read from the oscillator dial. The i-f amplifier is sharply tuned by a crystal filter or special feedback loops. In the RC-tuned type, an amplifier is tuned by means of variable resistance-capacitance networks, the frequency being read from the dial of the variable resistor(s) or capacitor(s). Each type of wave analyzer terminates in an electronic ac voltmeter/millivoltmeter which gives peak deflection when the instrument is tuned to the frequency of the incoming af signal.

The usual tuning range of the wave analyzer is 20 Hz to 20 kHz in several bands, although some of these instruments operate as high as 22 MHz in the rf spectrum. Depending upon make and model, the frequency accuracy varies from ±0.5% to ±1%, the input impedance from 100,000 ohms to 1 megohm, and the input-signal voltage range from 0.1 μV to 300 V.

B. Tuned null detector

This instrument is similar to the RC-tuned wave analyzer but has a somewhat less-complicated circuit. It is intended primarily as a frequency-selective null detector for ac bridges, and, like the wave analyzer, it is tuned for peak deflection of its indicating meter.

The tuning range of this instrument is 20 Hz to 20 kHz in several bands. The typical frequency accuracy is ±3%, the input impedance 50,000 ohms to 1 megohm, and the input-signal voltage range 0.1 μV to 200 V.

C. Tuned sound and vibration analyzer

This instrument, like the tuned null detector described in Part B, is also similar to the RC-tuned wave analyzer but has a somewhat simpler circuit. And, like the other two instruments, it is also tuned for a peak deflection of its indicating meter.

Typical ratings are: tuning range 2.5 Hz to 25 kHz, frequency accuracy ±2%, input impedance 25 megohms, and input-signal voltage range 0.3 mV to 30 V.

D. Distortion analyzer

Also called a *harmonic distortion meter,* this instrument—like the two immediately preceding ones—is a frequency-selective RC-tuned amplifier with a terminating electronic ac voltmeter/millivoltmeter. But, unlike all of the preceding instruments, it is tuned for dip, instead of peak deflection, of the meter.

Depending upon make and model of the distortion meter, the typical tuning range is 10 Hz to 1 MHz; the frequency accuracy ±3% to ±12%, depending upon the frequency range; the input impedance 1 megohm; and the input-signal voltage range 0.3 V to 300 V.

2.8 FREQUENCY-SELECTIVE RC CIRCUITS

Resistance-capacitance circuits are passive and relatively simple. Of importance is the fact that some of them can be made frequency sensitive, to give null response at a particular audio frequency which can be determined from the resistance and capacitance values at null. If a variable RC circuit has previously been frequency-calibrated, it makes a simple frequency-measuring device. There are many such circuits, also called *notch filters;* the principal ones are the *Wien bridge, twin-T network,* and *Hall network.* (The familiar *bridged-T circuit* has been passed over here because it gives a shallow null.) Use of these circuits is usually restricted to frequencies no higher than 20 kHz, since small stray reactances blunt the null response and may even bypass the signal around the circuit at higher frequencies.

These devices will usually be precalibrated so that an unknown frequency may be read directly from a dial when the device is balanced to null. In the absence of such a calibration, however, the frequency can be calculated (with the aid of Equations 2-1, 2-2, or 2-3, whichever applies) from the values of resistance and capacitance at null. The accuracy of this calculation is governed, of course, by the accuracy with which the R and C values can be determined.

The accuracy of any frequency-calibrated RC circuit used as a frequency meter depends upon:

1. Accuracy of the initial calibration.
2. Sharpness of the null (harmonics in the test signal broaden the null).
3. Closeness to which the dial can be reset.
4. Readability of the dial.
5. Sensitivity of the null detector.
6. Closeness with which the range-switching capacitors are matched.
7. Wearing and aging of the variable resistors.

At best, the accuracy is equal to that of the original calibration source; at worst, an error of 10% to 20% of the indicated frequency can be expected.

A. Wien bridge

See Fig. 2-14A. In this circuit, there are two resistance arms (R_1 and R_2) and two impedance arms (C_1R_3 and C_2R_4). The tuning component is the dual 10,000-ohm wirewound rheostat, R_3-R_4. (The resistance of these two sections must track closely.) Capacitances C_1 and C_2 are equal. The null detector may be headphones, ac electronic voltmeter, oscilloscope, or similar device.

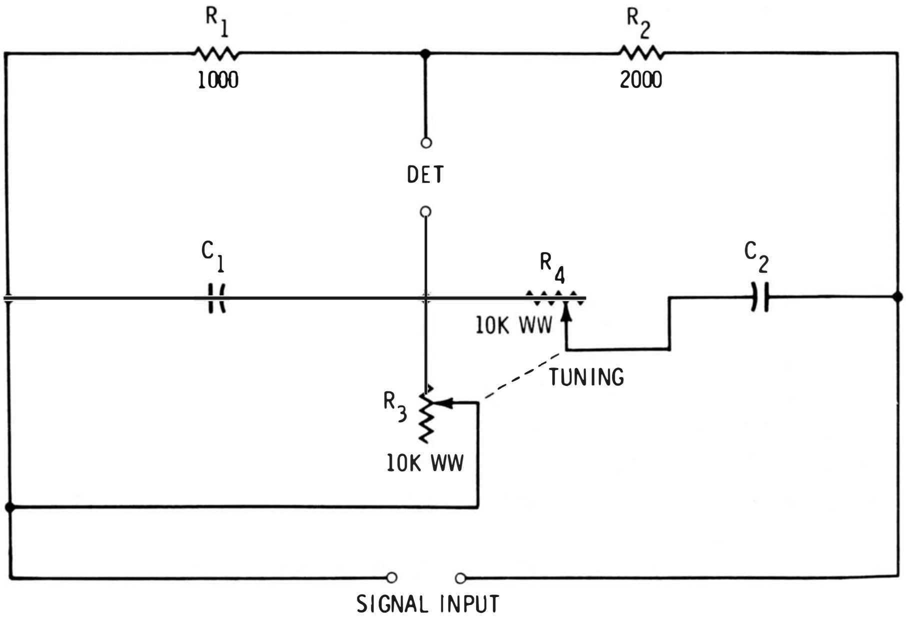
The null equation of the circuit is simplified when (as in Fig. 2-14A) R_2 is made twice R_1, $C_1 = C_2$, and $R_3 = R_4$ at all settings. At null:

$$f_x = 1/(6.28\ R_3C_1) \qquad \text{(Eq 2-1)}$$

where,

f_x is the unknown frequency in hertz,
R_3 is in ohms,
C_1 is in farads.

With the aid of an accurately calibrated audio generator, a dial attached to the dual rheostat may be calibrated to read directly in hertz. In the process, frequencies are chosen for as many dial points as practicable. At each frequency, the dual rheostat is set for null, and that frequency is inscribed on the



(A) Circuit.

RANGE	C_1 µF	C_2 µF	RANGE MULTIPLIER
200-200 Hz	0.796	0.796	X1
200-2000 Hz	0.0796	0.0796	X10
2-20 kHz	0.00796	0.00796	X100

(B) Performance.

Fig. 2-14. Wien bridge.

dial. When the device is subsequently used as a frequency meter, it is necessary only to apply the unknown-frequency signal, adjust the dual rheostat for null, and read the frequency from the dial.

In one rotation, the dual rheostat will cover a 10:1 frequency span. To change range, new values of C_1 and C_2 must be switched simultaneously in pairs into the circuit in place of the original capacitances. Fig. 2-14B shows the values that C_1 and C_2 must have for ranges of 20 to 200 Hz, 200 to 2000 Hz, and 2 to 20 kHz. If the six capacitors have the exact specified values, the dial will need calibration on only the lowest range, its readings being multiplied by 1, 10, or 100 (Fig. 2-14B).

When the signal source and the null detector both are power-line operated, hum interference may demand the use of an isolating transformer at either the input or the output of the bridge, to prevent the null point from being obscured. An input transformer should have an internal shield.

B. Twin-T network

See Fig. 2-15A. This circuit, also known as the *parallel-T network,* takes its name from the fact that it consists of two T's ($R_1R_2C_3$ and $C_1C_2R_3$) connected in parallel. It gives a complete null, and its passband is reasonably narrow if high-Q capacitors are used and if the network is driven from a low-impedance signal source and loaded with a high-impedance detector.

The behavior of the twin-T network is similar to that of the Wien bridge described in Part A, but its selectivity is significantly better and, unlike the Wien bridge, the twin-T permits a common ground between generator, network, and detector. The tuning component is the 3-gang wirewound rheostat, R_1-R_2-R_3 (the resistance of these sections must track closely). The null detector may be *crystal* headphones, ac electronic voltmeter, oscilloscope, or similar high-impedance device.

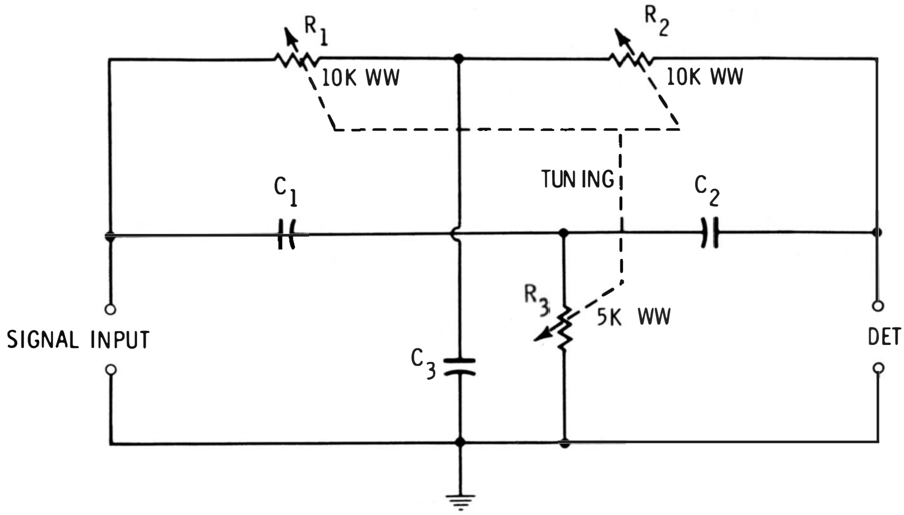
The null equation of the circuit is simplified by making $C_1 = C_2 = \frac{1}{2}C_3$, and $R_1 = R_2 = 2R_3$. Under these conditions, at null:

$$f_x = 1/(6.28\, R_1\, C_1) \qquad \text{(Eq 2-2)}$$

where,

f_x is the unknown frequency in hertz,
R_1 is in ohms,
C_1 is in farads.

With an accurately calibrated audio generator, the dial attached to the 3-gang rheostat may be calibrated to read directly in hertz. Frequencies are chosen for as many dial points as practicable. At each frequency, the rheostat is set for null, and that frequency is inscribed on the dial. When the device is subsequently used as a frequency meter, it is necessary only to apply the unknown-frequency signal, adjust the rheostat for null, and read the frequency from the dial.



(A) Circuit.

RANGE	C_1 µF	C_2 µF	C_3 µF	RANGE MULTIPLIER
20-200 Hz	0.796	0.796	1.59	X1
200-2000 Hz	0.0796	0.0796	0.159	X10
2-20 kHz	0.00796	0.00796	0.0159	X100

(B) Performance.

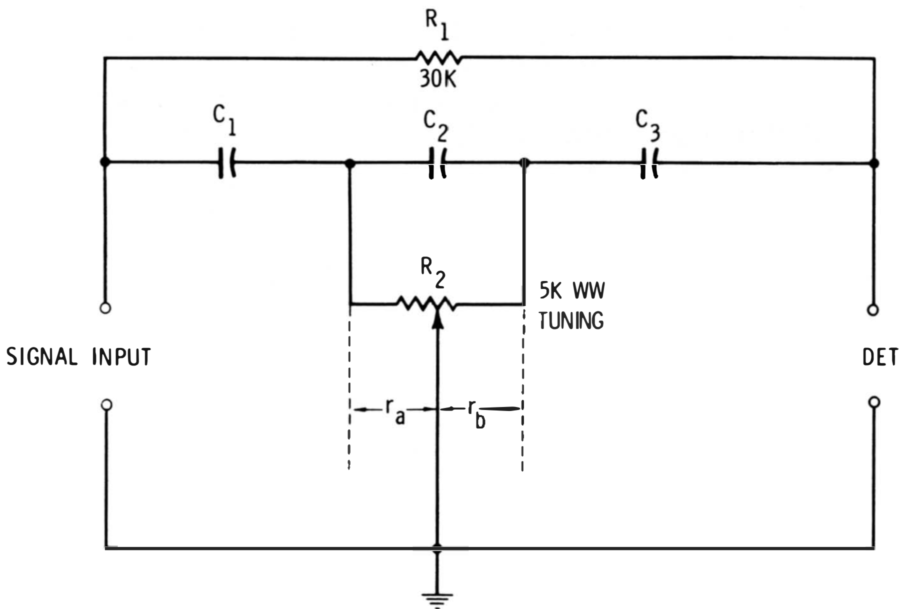
Fig. 2-15. Twin-T network.

In one rotation, the 3-gang rheostat will cover a 10:1 frequency span. To change range, new values of C_1, C_2, and C_3 must be switched simultaneously into the circuit in place of the original three capacitances. Fig. 2-15B shows the values that C_1, C_2, and C_3 must have for ranges of 20 to 200 Hz, 200 to 2000 Hz, and 2 to 20 kHz. If the nine capacitors have the exact specified values, the dial will need calibration on only the lowest range, its readings being multiplied by 1, 10, or 100, as shown in Fig. 2-15B.

Although the twin-T network is superior to some other RC null circuits used as audio-frequency meters, its need for three closely tracked rheostat sections and for accurate capacitors that must be switched in threes, causes it to be avoided in many instances.

C. Hall network

See Fig. 2-16A. This circuit, also known as the *bridged differentiator,* needs only one potentiometer (R_2) for tuning, but this simplicity is offset by the requirement that the capacitors (C_1, C_2, C_3) be switched simultaneously in threes to change



(A) Circuit.

RANGE	C_1 µF	C_2 µF	C_3 µF	RANGE MULTIPLIER
20-200 Hz	1.0	1.0	1.0	X1
200-2000 Hz	0.1	0.1	0.1	X10
2-20 kHz	0.01	0.01	0.01	X100

(B) Performance.

Fig. 2-16. Hall network.

frequency range. Like the twin-T network described in Part C, the Hall network provides a common ground between generator, network, and detector.

The relationship $C_1 = C_2 = C_3$ must be maintained in all frequency ranges. At null:

$$f_x = 1/(6.28\, C_1\sqrt{3r_a r_b}) \qquad \text{(Eq 2-3)}$$

where,

f_x is the unknown frequency in hertz,
C_1 is in farads,
r_a and r_b are in ohms.

On all bands, the bridging resistance has the same value: $R_1 = 6(r_a + r_b) = 30{,}000$ ohms.

With the aid of an accurately calibrated audio generator, a dial attached to the potentiometer may be calibrated to read directly in hertz. In the process, frequencies are chosen for as many dial points as practicable. At each frequency, potentiometer R_2 is set for null, and that frequency is inscribed on the dial. When the device is subsequently used as an audio-frequency meter, it is necessary only to apply the unknown frequency, adjust the potentiometer for null, and read the frequency from the dial.

In one rotation, potentiometer R_2 will cover a 10:1 frequency span. To change range, new values of C_1, C_2, and C_3 must be switched simultaneously into the circuit in place of the original three capacitors. Fig. 2-16B shows the values that the capacitors must have for ranges of 20 to 200 Hz, 200 to 2000 Hz, and 2 to 20 kHz. If the nine capacitors have the exact specified values, the dial will need calibration on only the lowest range, its readings being multiplied by 1, 10, or 100, as shown in Fig. 2-16B.

2.9 RESONANT LC CIRCUIT

When an accurate inductor (inductance L) and one or more accurate capacitor decades (total capacitance C) are available, they may be connected as a parallel-resonant test circuit, as shown in Fig. 2-17, for identifying audio frequencies. When a signal of unknown frequency is applied to this circuit through the isolating resistor (R), the circuit may be tuned by varying the capacitance furnished by the decade(s). At resonance, indicated by peak deflection of the meter, the unknown frequency may be calculated from the known inductance (L) and the total capacitance setting (C) of the decade(s). Thus:

$$f_x = 1/(6.28\sqrt{LC}) \qquad \text{(Eq 2-4)}$$

where,

f_x is the unknown frequency in hertz,
L is in henrys,
C is in farads.

Capacitor decades of suitable range must be employed to give a small-step variation of capacitance for close tuning. (A single laboratory-type capacitor decade can provide a total capacitance of 1.11111 μF in 1-pF steps.) When an inductor decade also is available, the flexibility of the method is increased. The tuning is sharp when the inductor and capacitors are high-Q components.

Procedure:

1. Set up the circuit, as shown in Fig. 2-17.
2. Adjust the capacitor decade(s) for resonance, as indicated by the peak deflection of the meter.
3. Read the corresponding capacitance (C) from the setting of the capacitor-decade dials.
4. Use this capacitance and the inductance (L) of the standard inductor to calculate unknown frequency f_x with Equation 2-4.

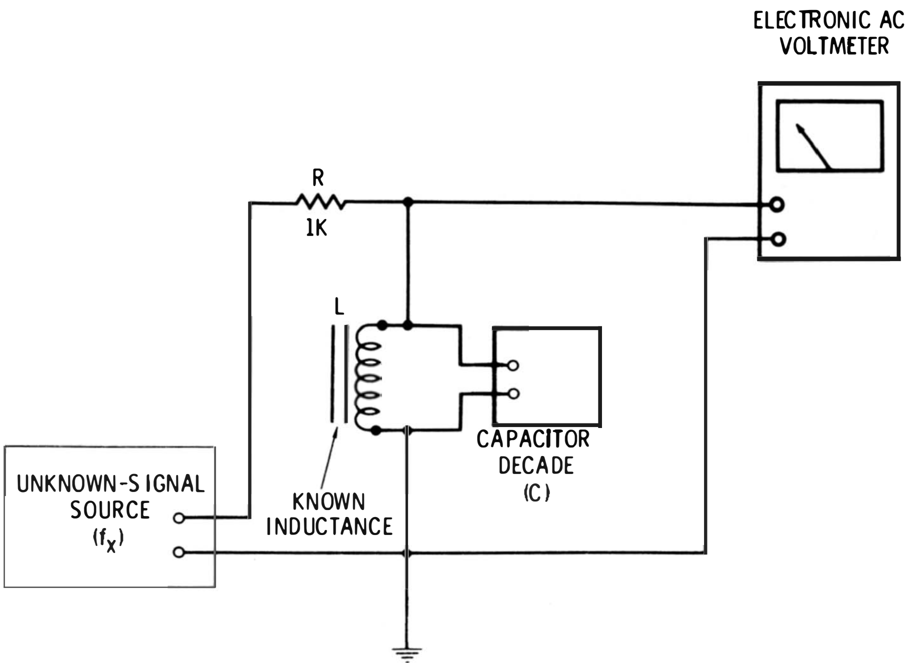


Fig. 2-17. Resonant circuit.

5. If the resonance is not obtained at any capacitance, change the inductor to one of different inductance and repeat Steps 1 through 3.

Illustrative example: When a 1.32-H inductor is used in the test setup, resonance is obtained with a capacitance of 0.0053 μF. Calculate the unknown frequency.

Here, $L = 1.32$, and $C = 5.3 \times 10^{-9}$. From Equation 2-4, $f_x = 1/(6.28\sqrt{1.32(5.3 \times 10^{-9})}) = 1/(6.28\sqrt{6.99 \times 10^{-9}}) = 1/[6.28(8.36 \times 10^{-5})] = 1/(5.25 \times 10^{-4}) = 1905$ Hz

This is a simple method of frequency measurement analogous to the absorption wavemeter method employed at radio frequencies. Its accuracy is hampered, however, especially at the higher frequencies, by indeterminate stray capacitance present in the setup even when the shortest possible leads are used. A further disadvantage results from self-resonance in the inductor. In search of such resonance(s), the circuit should be inspected preliminarily with the capacitors disconnected, a signal applied from a variable-frequency audio generator, and the latter tuned from 20 Hz through 30 kHz. A self-resonant point will be indicated by peak deflection of the meter, and the frequency can be read from the dial of the generator. Ideally, the inductor would have no self-resonant point inside the intended range of frequency measurement.

In spite of its shortcomings, this method of frequency checking is useful when more-sophisticated equipment is unavailable. But, unless laboratory-type inductors and capacitors are employed and corrections made for stray and distributed capacitance, frequency error may run as high as 10% to 25%.

CHAPTER 3

RADIO-FREQUENCY MEASUREMENT

Some of the techniques of audio-frequency measurement may also be used—with suitable modifications—for radio frequencies. By and large, however, measurements in the rf spectrum require special instruments and methods. This chapter describes 16 methods or devices, including microwave techniques.

Since many radio-frequency measurements demand precautions not always needed at lower frequencies, the reader should study Section 3.1 before proceeding further into the chapter.

3.1 SPECIAL PRECAUTIONS AT RADIO FREQUENCIES

It is well known that radio-frequency tests are fussier than those at audio frequencies. The large frequency changes resulting from small changes of inductance and capacitance, the high susceptibility of circuits to stray coupling, the confusion of harmonics and fundamental frequencies, the drift of operating points, and the effectiveness of even small values of stray reactance are among the factors that combine to make high-frequency tests exacting. The following paragraphs discuss 12 areas that merit attention in radio-frequency measurement.

A. Leads

All wire leads must be kept as short and straight as possible, to minimize inductance and stray coupling. They should also be as thick as practicable. In audio-frequency test setups, leads of longer length often introduce no difficulty; at radio frequencies, however, length cannot be ignored (at 50 MHz, for example, a straight, 10-inch length of No. 22 copper wire has a reactance of approximately 94 ohms). Always use the shielded cables that are supplied with signal generators and other types of rf equipment.

B. Grounding

A common point ("ground") to which the return circuit of each instrument or device in the test setup is connected is often essential. All returns should run to this one point which itself should be connected to earth (a cold-water pipe is satisfactory). See, for example, Fig. 3-5. Avoid a number of separate ground points, even when they are wired together; they increase the probability of cross coupling.

C. Bypassing, choking, shielding

For reliable operation, test setups must contain bypass capacitors and rf chokes at the right points. When shown in the diagrams, these components should not be omitted. Some components or stages also require shielding (see Part D, "Body capacitance").

D. Body capacitance

In some setups, hand capacitance can detune a circuit or reduce signal level. Body-capacitance effects should be eliminated —or at least minimized—through the use of tuning wands, adequate grounding and shielding, and other such measures before serious measurements are made. When the setup will permit none of these strategies, the measurements or calculations must be corrected for body-capacitance errors which must be determined in preliminary dry runs of a test.

E. Drift

Frequency drift in instruments and test circuits is often more noticeable at radio frequencies than at audio frequencies. Common causes of this drift are temperature change, operating voltage change, and aging of components. Short-term drift for all instruments and by employing voltage-regulated power supplies (in critical, sophisticated tests, it may be necessary to make all measurements at a constant ambient temperature). Long-term drift, usually resulting from aging and from battery rundown, is circumvented by frequent recalibration of instruments and regular replacement of batteries and deteriorated components.

F. Radio interference

Some test setups, particularly those containing sensitive rf instruments, pick up broadcast signals. The circuit should be inspected beforehand for this condition whenever tests are planned on, or are close to, radio or tv frequencies or their harmonics. Adequate shielding and grounding of the test circuit will usually eliminate this nuisance. Sometimes, however, signals arrive via the power line acting as an antenna, and pass through line-operated instruments into the test circuit; and in this instance a power-line rf filter is required. In stubborn cases of radio-tv interference, all work must be done in a shielded booth.

G. Noise pickup

Some test setups, particularly those containing sensitive rf instruments, pick up electrical noise. This nuisance usually can be minimized by short leads, good shielding, and use of suitable power-line filters. In stubborn cases, however, the only remedy is to disable the noise source, use a shielded room, or change the test location.

H. Harmonics

In some measurements of radio frequency, there is the ever-present danger of working with the wrong signal. Instead of a desired fundamental frequency, for example, a harmonic or subharmonic of either (or both) the standard signal or the unknown signal may inadvertently be used. Conventional checking procedures should be employed to prevent this gross error.

I. Loose coupling

Tight coupling between a signal source and a frequency-measuring device tends to broaden the response of the device and thus reduce the accuracy of the measurement. It can also shift the frequency, especially when the signal source is a self-excited oscillator. For best accuracy and cleanest operation, therefore, the loosest practicable coupling should always be employed.

J. Multiple instruments

Insofar as it is practicable, a single instrument should be used throughout a particular test, since there is often some inaccuracy in the overlap of separate instruments. When the use of several instruments is unavoidable, they should be inspected beforehand for agreement, and all subsequent measurements should be corrected for any instrument errors that are noted.

K. Frequency units

To forestall confusion and error, frequencies throughout a single test should be kept in the same units: Hz, kHz, MHz, GHz. It is not always possible to avoid a mixture, since different instruments used in a single test may indicate frequency in different units, and since a single instrument may employ different units in different ranges. Where separate units are unavoidable, they must be carefully recorded in the data; and before making a set of calculations, it is advisable first to convert all of them to one class of unit.

L. Recalibration

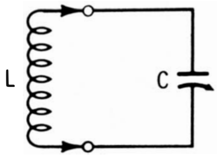
The calibration of radio-frequency instruments must be checked at regular intervals, and any needed adjustments should be made to maintain accuracy. Some instruments, such as signal generators, have a self-contained frequency standard —usually a 100-kHz crystal oscillator—which allows periodic checking of the tuning dial at many points. Others must be checked against an external standard, either on the user's premises or at the instrument manufacturer's factory or at a private laboratory.

M. Exposure to fields

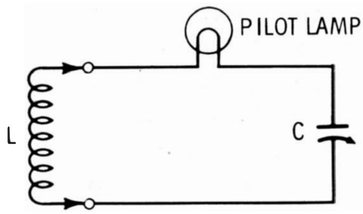
Strong rf fields, especially at microwave frequencies, might possibly be injurious to the operator. We lack sufficient data concerning the effects of this radiation on the human body, particularly the skin and eyes, to make indictments at this time. In the absence of such information, however, it seems prudent to avoid unnecessary, prolonged exposure to high-frequency fields. Make tests as quickly as practicable, and even then keep as clear of the field as possible.

3.2 SIMPLE ABSORPTION WAVEMETER

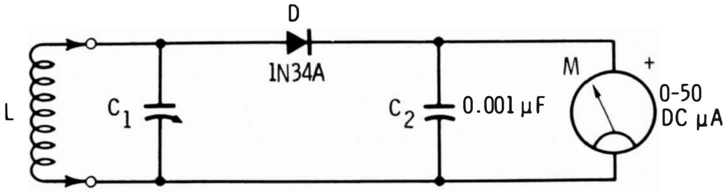
The absorption wavemeter (see basic circuit in Fig. 3-1A), also called an *absorption frequency meter,* is so called because it absorbs a small amount of rf energy from the unknown-frequency source to which it is coupled. Basically, the instrument is a simple tuned circuit consisting of a fixed-inductance coil (L) and a variable capacitor (C). The wavemeter is tuned to resonance at the unknown frequency (f_x) by adjusting the capacitor, and at resonance, f_x is read from the calibrated dial



(A) Basic circuit.

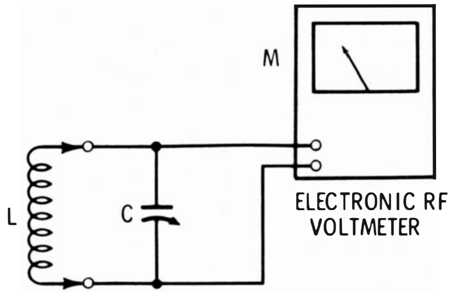


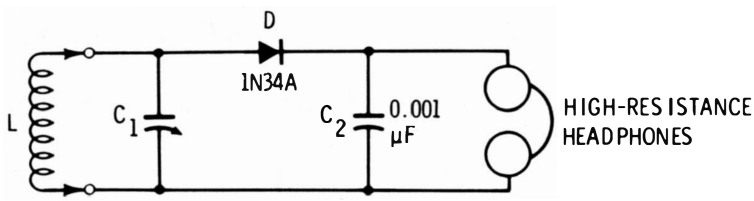
(B) Self-contained indicator.



(C) Rectified signal and dc meter.

(D) Electronic rf voltmeter as indicator.





(E) Diode demodulates rf and headphones are used for indicator.

Fig. 3-1. Absorption wavemeters.

of the capacitor. The frequency range is changed by plugging-in a different coil.

Table 3-1 gives coil winding data for a wavemeter employing a 140-pF tuning capacitor. The four coils cover a total frequency span from 1.1 to 150 MHz in four bands. Other inductance and capacitance combinations may be worked out for other frequencies.

In use, the wavemeter is *loosely* coupled to the unknown-frequency source and tuned for resonance. For instance, the instrument may be held so that coil L is close to the output coil of a radio transmitter. Resonance can be indicated in various ways. When the circuit in Fig. 3-1A is used, for example, the unknown-signal source must have a current meter in its output stage (a plate milliammeter in a tube-type source, a collector milliammeter in a transistor-type source); and the deflection of this meter will rise sharply as the wavemeter is tuned, the peak point of this rise indicating resonance. In the other arrangements, the wavemeter has a self-contained indicator. In Fig. 3-1B, this is a pilot lamp such as the 2-V, 60-mA Type 48. The lamp glows brightest at resonance. This arrangement can be used only when the signal source supplies enough power to light the lamp. In Fig. 3-1C, a 1N34A germanium diode (D) rectifies the rf energy and deflects a 0 to 50 dc microammeter (M), the peak deflection of this meter indicating resonance. In Fig. 3-1D, an electronic rf voltmeter (vtvm or tvm) is connected temporarily to the wavemeter and indicates resonance by peak deflection. In Fig. 3-1E, a 1N34A germanium diode (D) demodulates an *amplitude-modulated* unknown-frequency signal and applies the resulting audio voltage to high-resistance headphones. Here, resonance is indicated by the loudest sound. Of these arrangements, the sharpest-tuning wavemeters are Fig. 3-1A, 3-1C, and 3-1D in that descending order. The least selective is Fig. 3-1B.

In wavemeters containing an internal indicator (e.g., Fig. 3-1B, 3-1C, 3-1D, and 3-1E), selectivity may be improved somewhat by tapping the indicator circuit down coil L to minimize loading of the tuned circuit. This then calls for a 3-terminal plug-in coil.

A wavemeter may be calibrated from an accurate rf oscillator or signal generator by coupling to that device and tuning the wavemeter to resonance successively at various frequencies

Table 3-1. Wavemeter Coil Data

	Variable Capacitor C = 140 pF
(A) 1.1–3.8 MHz	72 turns No. 32 enameled wire closewound on 1″ diameter plug-in form.
(B) 3.7–12.5 MHz	21 turns No. 22 enameled wire closewound on 1″ diameter plug-in form.
(C) 12–39 MHz	6 turns No. 22 enameled wire on 1″ diameter plug-in form. Space to winding length of 3/8″.
(D) 37–150 MHz	Hairpin loop of No. 16 bare copper wire. Spacing of 1/2″ between straight sides of hairpin. Total length including bend: 2 inches.

of the generator. Use as many frequencies as it is possible to inscribe on the dial without crowding. Usually, a separate dial scale is required for each range of the wavemeter (A, B, C, and D in Table 3-1). The wavemeter shown in Fig. 3-1A has no indicator of its own. It may be connected in series with the "high" lead between the generator and an all-band radio receiver. The wavemeter will then act as a wavetrap, eliminating the signal from the receiver at resonance.

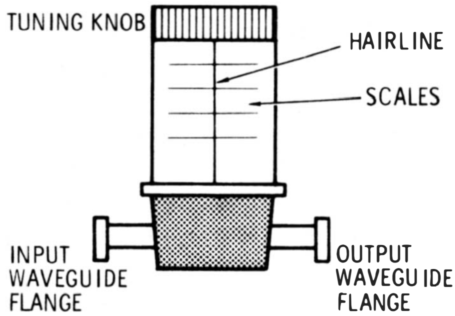
Professional, laboratory-type absorption wavemeters, once available with as good as 0.25% accuracy, are no longer manufactured. Most simple absorption wavemeters today are homemade. The accuracy of these latter instruments depends upon (1) accuracy of original calibration, (2) resettability of dial, (3) readability of dial, (4) sharpness of resonance, and (5) freedom from body-capacitance effects. An accuracy of ±10% would be considered good.

In spite of its shortcomings, the absorption wavemeter is very useful for determining approximate frequency. When very loosely coupled to a signal source, this instrument is insensitive to harmonics, unless the source is high powered, and therefore is not subject to confusion of frequencies. Moreover, the wavemeter is small (therefore easily hand-held and easily poked into close quarters) and, in addition, it requires no power supply.

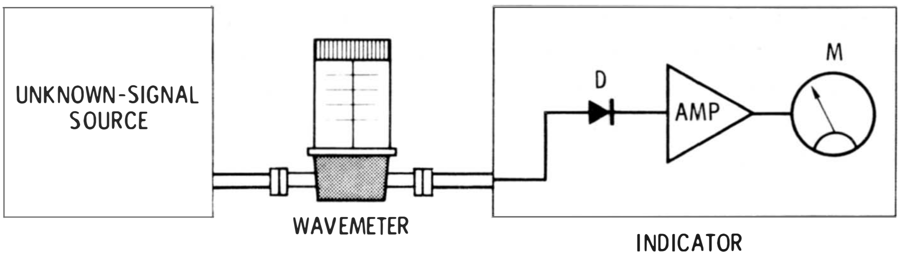
3.3 MICROWAVE WAVEMETER

This instrument (see Fig. 3-2) also called a *microwave frequency meter,* is somewhat similar in action to the absorption wavemeter described in Section 3.2. Employing neither inductance nor capacitance, it consists essentially of a high-Q resonant cavity tuned by means of a choke plunger. Microwave energy of unknown frequency is fed into the cavity via a waveguide fixture and out of the cavity via a similar fixture (another model of this instrument provides coaxial input and output). This arrangement allows the instrument to be inserted into a waveguide system or a coaxial system. The indicator (Fig. 3-2B) contains a silicon diode (D) which rectifies the output of the wavemeter, a dc amplifier (AMP) which boosts the resulting dc output of the diode, and a dc milliammeter (M) which is deflected by the output of the amplifier. When the wavemeter is tuned to resonance, the deflection of the meter (M) dips sharply, and the unknown frequency then may be read directly in gigahertz from the spiral scale of the wavemeter dial.

The microwave wavemeter is supplied for a single frequency range with a frequency ratio varying from 1.42:1 to 4.37:1, depending upon range. A set of such instruments, such as the eight units in the Hewlett-Packard 530 group, gives a frequency coverage from 0.96 GHz to 40 GHz, with an overall accuracy of 0.065% to 0.17%, depending upon individual range.



(A) Instrument.



(B) Test setup.

Fig. 3-2. Microwave wavemeter.

3.4 LECHER FRAME

For frequencies between 900 MHz and 15 GHz, measurements can be made in terms of the wavelength of standing waves set up along two parallel rods or wires by the unknown-frequency source. The parallel-wire contrivance is termed a *Lecher frame* (see Fig. 3-3). The wires (No. 12 or heavier bare copper wire) are each 2 feet long in their straight portion and are spaced about 1 inch apart. They are mounted solidly on standoff insulators on an insulating base and bent into a loop at one end for inductive coupling to the unknown-frequency source. The standing-wave detector is a radio-frequency meter consisting of a 1N21B silicon diode (D) and a 0 to 50 dc microammeter (M). This detector is mounted on a simple sliding carriage so that it can be positioned at, and make contact with, any desired point along the length of the wires. If the signal source delivers at least 1/4 watt of rf power, the indicator can be simply a 2-V, 60-mA pilot lamp.

When rf energy from the signal source is coupled into the frame, standing waves appear along the wires. As the detector then is slid along the wires, meter **M** deflects upward to show high-voltage points (maxima) in these waves and downward to show low-voltage points (minima). The operator carefully

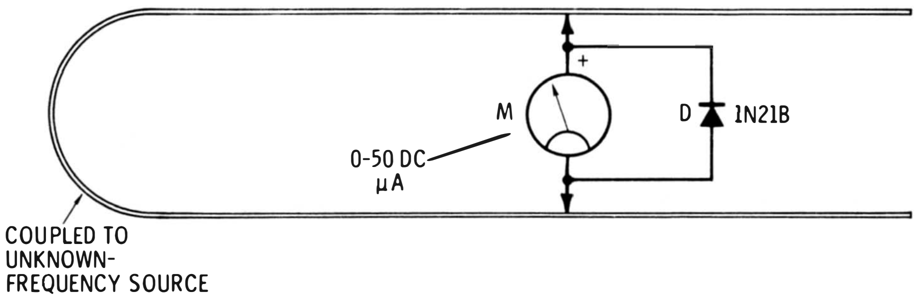


Fig. 3-3. Lecher frame.

measures the distance, d, in centimeters, between any two successive maxima or successive minima. (This gives the wavelength of the unknown signal, in centimeters.) The unknown frequency then is calculated from this wavelength:

$$f_x \text{ in MHz} = 300{,}000/d \qquad \text{(Eq 3-1)}$$

$$f_x \text{ in GHz} = 30/d \qquad \text{(Eq 3-2)}$$

Illustrative example: In a certain test with a Lecher frame, peak deflections are obtained at 10.5 cm and 16 cm along a scale permanently mounted on the frame. Calculate the frequency in megahertz.

Here, $d = 16 - 10.5 = 5.5$ cm. From Equation 3-1, $f_x = 300{,}000/5.5 = 54{,}545$ MHz.

In the first paragraph, 900 MHz is suggested as the lowest frequency for this method. This limit is based upon the 2-ft length recommended for the wires. Setups with longer wires or rods lack the mechanical stability required for the Lecher frame. Also, at lower frequencies (longer wavelengths), the maxima and minima on the long wires become broad and hard to pinpoint. (In a 50-MHz system, the correct response points would be 19.7 feet apart.)

Accuracy of this method depends upon (1) accuracy of the centimeter measurement, (2) sharpness of maxima or minima indication, (3) extent of body capacitance, (4) looseness of coupling, and (5) care in the calculation. A value of 10% is realistic.

3.5 SLOTTED LINE

At microwave frequencies, the *slotted line,* used primarily for other purposes, is a useful device for frequency measurement. Fig. 3-4 shows a test setup incorporating this device. The slotted line is essentially a special section of coaxial line; as such, it consists of an outer metal cylinder and an inner, concentric metal rod. A lengthwise slot is cut in the outer cylinder (the device takes its name from this), and a carriage is positioned to slide along the outside of this cylinder, carrying a metal probe which dips down into the space between the rod and the inner wall of the cylinder to sample the standing waves inside the cylinder. Inside the carriage, the probe is connected to a silicon point-contact diode (D). Although coaxial input and output coupling and a coaxial-type slotted line are shown in Fig. 3-4, *slotted waveguides* with waveguide-type coupling also are available.

When the slotted line is properly terminated and is adjusted by means of its tuning stub, rf energy from the unknown-frequency signal source sets up a standing-wave pattern inside the cylinder. As the carriage is slid along, the probe passes through high-voltage points (maxima) and low-voltage points (minima). These points are indicated by a detector consisting of diode D, the dc amplifier, and microammeter M; the meter deflects upward for maxima and downward for minima. A pointer on the carriage travels along a centimeter scale, allowing the operator to note the exact positions of these response points. From the distance between two successive maxima or two successive minima (which indicates the wavelength of the signal, in centimeters), the unknown frequency can be calculated in megahertz with Equation 3-1 or in gigahertz with Equation 3-2.

The characteristic impedance of the slotted line is usually 50 ohms. Depending upon make and model, the scale is accurate to ±0.1 mm, and this is the accuracy with which the wavelength may be measured. Depending upon make and model, the slotted line may be used between 300 MHz and 8.2 GHz.

3.6 SIGNAL-GENERATOR METHOD

An accurate rf signal generator may be employed to check unknown frequencies by means of the beat-note method. Fig.

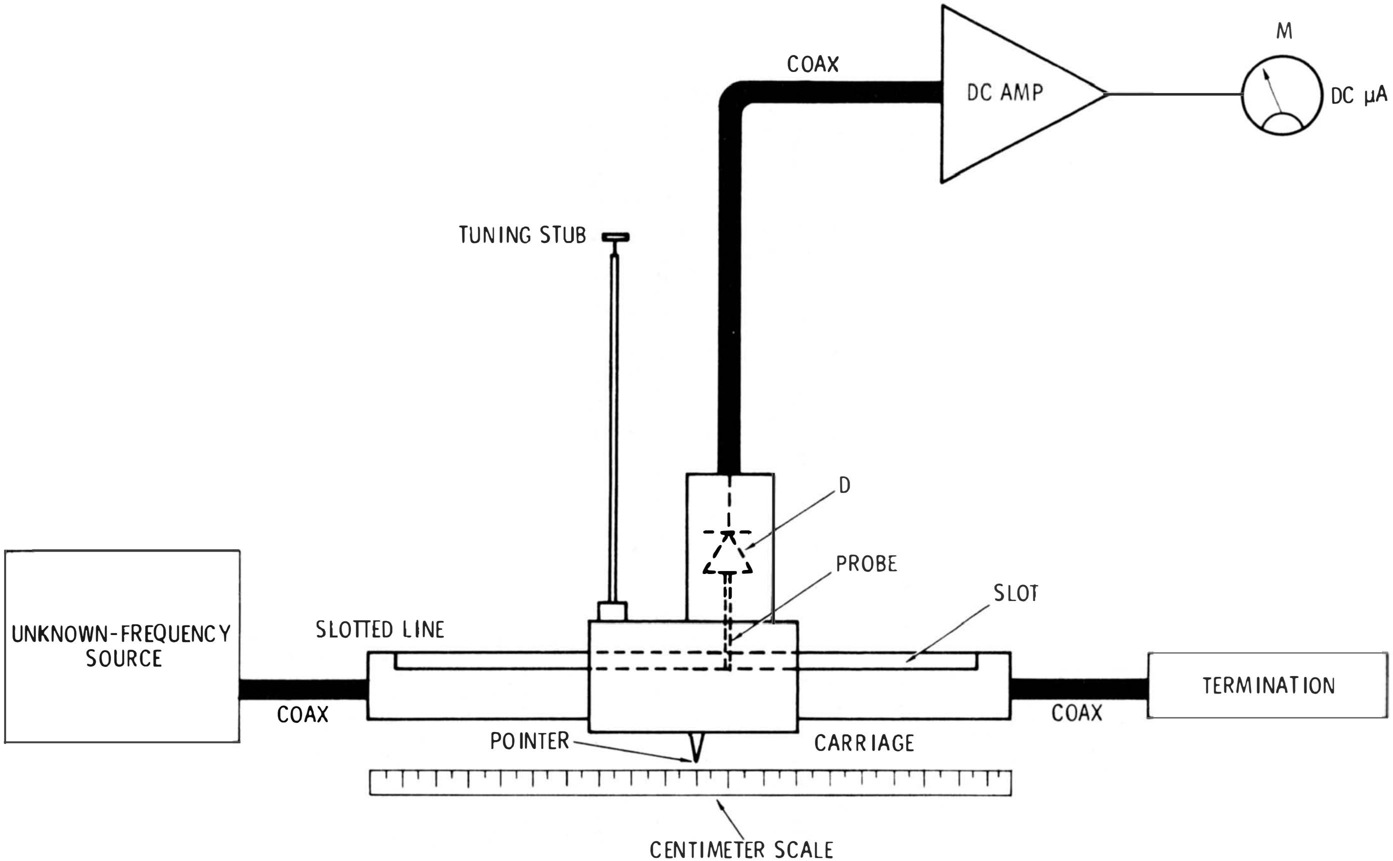


Fig. 3-4. Slotted line.

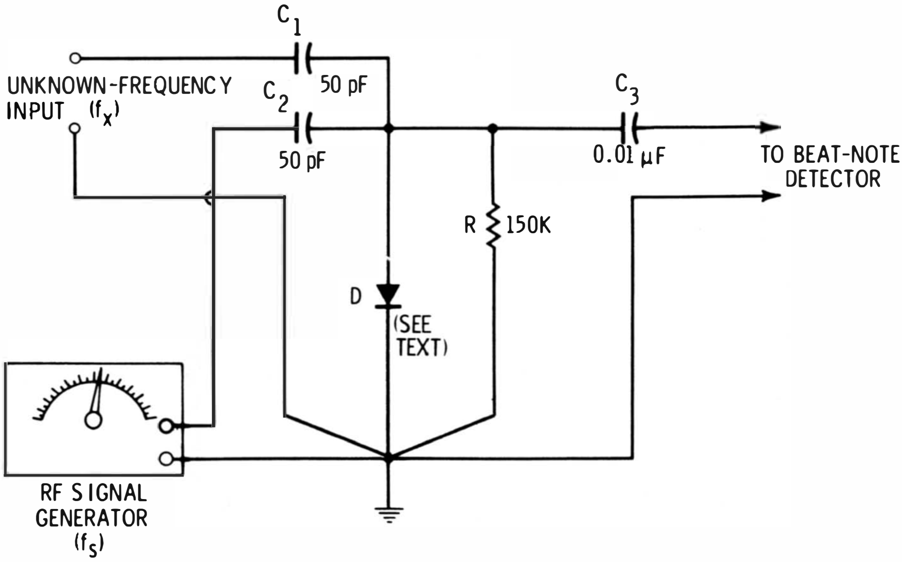


Fig. 3-5. Signal-generator method of rf measurement.

3-5 shows the test setup. In this arrangement, the signal of unknown frequency (f_x) and the generator signal (f_s) are applied simultaneously to a diode mixer circuit, and the resulting beat note between the two signals is delivered by the mixer to a beatnote detector. This detector can be an electronic ac voltmeter (vtvm or tvm), high-impedance headphones (with or without an audio amplifier), or an electronic audio-frequency meter (see Sections 2.4 and 2.5, Chapter 2). The generator is tuned to zero beat with the known signal, and at that point, f_x is read directly from the generator tuning dial. For frequency measurement as far as 30 MHz, a germanium point-contact diode, such as Type 1N34A, will be satisfactory for D in Fig. 3-5. At higher frequencies, a silicon point-contact diode, such as Type 1N21B, must be used.

Best results are obtained with a visual detector (electronic voltmeter or frequency meter), since the relatively poor low-frequency response of headphones makes the exact point of zero beat hard to pinpoint by ear. In Fig. 3-5, the standard-frequency source is variable, and the unknown-frequency source fixed, but the opposite arrangement also is feasible.

When the zero-beat point is sharply defined, the accuracy of this method can equal that of the signal generator.

3.7 HETERODYNE FREQUENCY METER

This instrument combines in one unit the separate sections used in the signal-generator method described in Section 3.6.

Fig. 3-6 shows a functional block diagram of the conventional heterodyne frequency meter. In this arrangement, an internal, highly stable variable-frequency rf oscillator (B) with frequency-reading dial is tunable over a single fixed range (say, from 500 kHz to 1000 kHz), and the output of this local oscillator is applied to a mixer (A) simultaneously with the signal of unknown frequency, f_x. The resulting beat note is presented to the zero-beat detector and indicator (C).

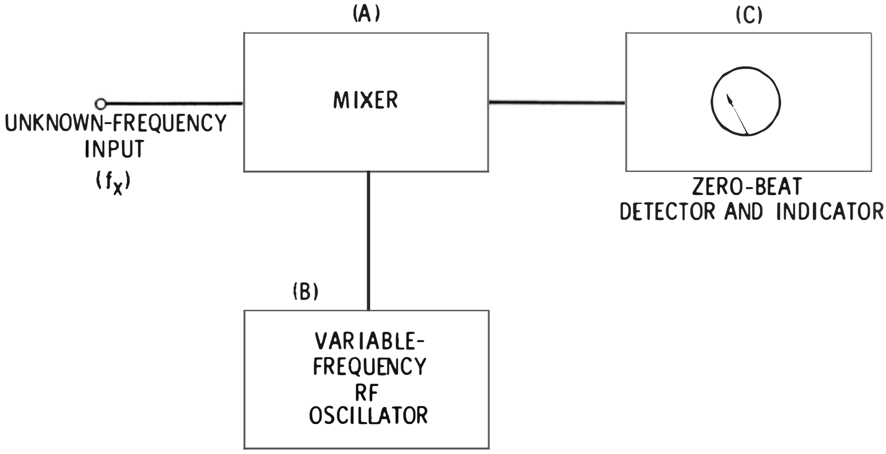


Fig. 3-6. Heterodyne frequency meter.

To check unknown frequency f_x, the operator tunes the oscillator to zero-beat with the unknown and reads the frequency directly from the dial. This assumes, of course, that f_x lies within the basic tuning range of the oscillator. But zero beat can be obtained also when f_x is a harmonic or subharmonic of the oscillator setting. This situation allows frequencies both above and below the fundamental range of the oscillator to be measured. Thus, if the oscillator tunes from 500 kHz to 1000 kHz and zero beat occurs at 625 on the dial, f_x could be 208.3 kHz, 312.5 kHz, 625 kHz, 1250 kHz, 1875 kHz, 2500 kHz, and so on. While it is this feature that gives the heterodyne frequency meter its wide range while employing only a single-range oscillator, it also invites error in frequency identification. For this reason, the operator must determine whether he is zero-beating the fundamental, a harmonic, or a subharmonic. With strong f_x signals, an instrument with 500- to 1000-kHz basic tuning range can be useful from 50 kHz to 50 MHz. Accuracy of the instrument depends upon that of the oscillator and may be as good as 2% of the indicated frequency at fundamentals and progressively worse as the harmonic number increases.

In another type of heterodyne frequency meter, the output of the mixer is an intermediate-frequency signal which is amplified by a sharp i-f amplifier and detected by a second detector. The dc output of the latter then actuates the indicating meter. When using this arrangement, the instrument is tuned for a peak deflection of the meter, instead of for a zero beat.

Some rf signal generators are equipped with a built-in mixer and headphone jack, to provide a heterodyne frequency meter for f_x measurement. The several separate bands of the signal generator enable all frequency measurements over a wide span to be made on fundamental frequencies.

3.8 DIP METER

This small, hand-held instrument, also known as a *grid-dip oscillator* in its tube version, is a standby with amateurs and experimenters. It is essentially a wide-band, variable-frequency rf oscillator with direct-reading dial and microammeter resonance indicator. Most dip meters have a special switch for disabling the internal power supply (while keeping the filament burning in the tube version). This converts the instrument into a direct-reading absorption wavemeter (see Section 3.2 for use of the wavemeter). Resonance is indicated by peak deflection of the microammeter. The dip meter can also be used with power *on* to measure frequency by the zero-beat method if high-resistance magnetic headphones are plugged into the phone jack of the instrument. In this latter application, the instrument is operated in the same way as an absorption wavemeter, but the resonance indication is an audible indication of zero beat.

Depending upon make and model, dip meters—by employing a series of plug-in coils—cover the frequency span of 72 kHz to 300 MHz. Special types extend the frequency limit upward to 940 MHz and downward to 50 kHz. The dip meter is not intended to be a precision instrument, and most manufacturers give no accuracy figure for this device (those who do, specify $\pm 3\%$).

3.9 ANALOG-TYPE ELECTRONIC FREQUENCY METER

This type of instrument, which offers high input impedance, employs a D'Arsonval-type meter for direct indications of frequency and requires no tuning. It is described in sufficient detail in Section 2.4, Chapter 2 (which see).

This instrument originally was intended for audio-frequency measurements only, and 100 kHz was its maximum frequency. Improved circuit design and modern manufacturing techniques, however, have greatly extended its frequency range. One modern instrument (Hewlett-Packard Model 5210A), for example, directly indicates frequencies from 3 Hz to 10 MHz in six bands: 0 to 100 Hz, 0 to 1 kHz, 0 to 10 kHz, 0 to 100 kHz, 0 to 1 MHz, and 0 to 10 MHz. The last three bands, of course, are of interest to the worker with radio frequencies. Accuracy is 1% of reading from 10% of full scale up.

While the analog-type frequency meter has been largely superseded by the digital type, the former is still valued in those applications in which a quick appraisal of up and down movements of frequency is desired (this is somewhat difficult to keep track of with the digital readout).

3.10 DIGITAL-TYPE ELECTRONIC FREQUENCY METER

The digital electronic counter is useful as a frequency meter at radio frequencies, as well as at audio frequencies where it is employed so widely. The general principles of this instrument

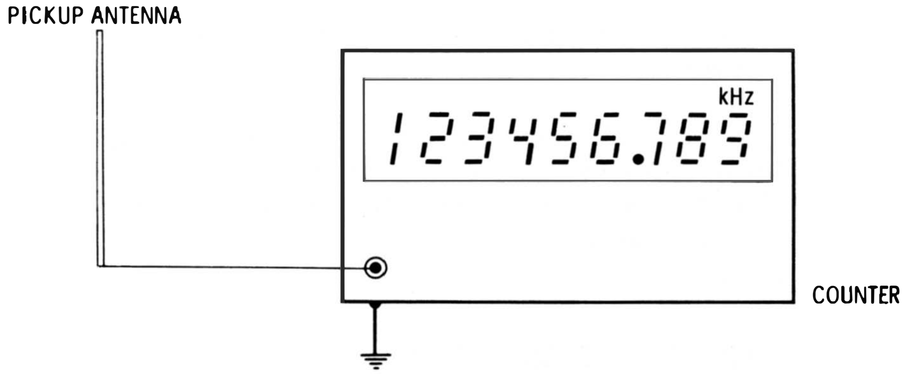


Fig. 3-7. Digital-type electronic frequency meter.

are explained in Section 2.5, Chapter 2 (which see). Radio-frequency energy from the unknown-frequency signal source may be introduced into the instrument either through a series capacitor or through a small pickup antenna plugged into the input receptacle (see Fig. 3-7), or by means of a small pickup coil of a few turns.

Depending upon make and model, electronic counters give a direct display in either hertz, kilohertz, megahertz, or gigahertz up to 18 GHz and in 6, 8, 9, or 10 digits with the decimal point automatically placed. Input impedance is 50 ohms, 1 megohm, or both. Sensitivity ranges from 10 mV to 35 mV rms sine wave, accuracy is ±1 digit ± the time-base error.

The digital counter has become increasingly popular as a frequency meter because its operation is instant and automatic and because it can display a number of digits for the close reading of frequency.

3.11 WAVE ANALYZER

The *wave analyzer* is an instrument intended primarily for the evaluation of a signal and its various harmonics. However, since it is continuously tunable with a dial reading directly in frequency units, this instrument is useful also as a frequency meter. The wave analyzer is tuned simply for peak deflection of its self-contained electronic voltmeter, and the frequency then is read directly from the dial. The operating principle of the wave analyzer is explained in sufficient detail in Section 2.7A, Chapter 2 (which see).

The conventional wave analyzer is designed for the 20-Hz to 20-kHz range. However, the operation of some modern models extends high into the radio-frequency spectrum. A tuning range of 1 kHz to 18 MHz in 18 overlapping bands thus is provided by one model (Hewlett-Packard 312A) with digital electronic readout (accuracy is ±10 Hz + the time-base accuracy).

Within its range, the wave analyzer can be used as a sharp-tuning continuously variable frequency meter which will show not only the unknown radio frequency, but also the signal amplitude. It will also, by its nature, evaluate each of the harmonics of the signal.

3.12 OSCILLOSCOPE METHODS

High-frequency oscilloscopes can be used to some extent for the measurement of radio frequency. The principal methods are described below.

A. Oscilloscope having calibrated time base

Modern factory-built oscilloscopes and some kit-type oscilloscopes, as well, come equipped with a calibrated horizontal sweep system which can be read directly in seconds, milliseconds, microseconds, or nanoseconds per centimeter or per screen division from the settings of front-panel selectors and multipliers. These instruments provide a number of ranges, such as 10 ns/div, 0.2 μs/cm, 100 ms/cm, and 1 s/div. It is not uncommon for one instrument to provide as many as 20 selectable rates. Accuracy is usually ±3% to ±5%. The period (t) of 1 cycle of an unknown frequency is easily found by measuring the time width of this cycle along the horizontal axis, and from this, the frequency is calculated:

$$f_x = 1/t \qquad \text{(Eq 3-3)}$$

where,

f_x is in hertz,
t is in seconds.

Illustrative example: When the sweep rate of a certain oscilloscope is adjusted to 100 ns/cm, 1 stationary cycle of the applied unknown-frequency signal is 3.3 cm wide. Calculate the frequency in megahertz.

Here $t = 3.3\,(100)$ ns $= 330$ ns $= 3.3 \times 10^{-7}$ s.
From Equation 3-3, $f_x = 1/3.3 \times 10^{-7} = 3.03 \times 10^{6}$ Hz $= 3.03$ MHz.

Some sophisticated, laboratory-type oscilloscopes give a direct, automatic readout of 1/t, i.e., of frequency, thus obviating the need for any calculations.

B. Use of Lissajous figures

When the horizontal channel, as well as the vertical channel, of an oscilloscope will handle radio-frequency signals, a radio-frequency signal generator or frequency standard may be employed to identify unknown frequencies by using Lissajous figures. The accuracy of this method can equal that of the generator.

Except for the precautions which apply to any rf test (see Section 3.1) and for the higher frequencies involved, the techniques for Lissajous figures at radio frequencies are the same as for audio frequencies. These are explained in Section 2.6B, Chapter 2, and the reader is referred to that section for instructions and sample patterns.

C. Use of individually calibrated screen

Except for the precautions which apply to any rf test (see Section 3.1) and for the higher frequencies involved, the procedure for radio-frequency checking with an individually calibrated screen is the same as for audio frequencies. The technique is explained in Section 2.6F, Chapter 2, and the reader is referred to that section for instructions and sample patterns.

D. Use of dual-trace oscilloscope

Except for the precautions which apply to any rf test (see Section 3.1) and for the higher frequencies involved, the procedure for radio-frequency checking with a dual-trace oscilloscope is the same as for audio frequencies. The technique is explained in Section 2.6F, Chapter 2, and the reader is referred to that section for instructions and a sample pattern.

3.13 RADIO RECEIVER

An all-band radio receiver is useful as an emergency, wide-range radio-frequency meter. A communications-type receiver may be tuned for peak deflection of its self-contained S meter; in other receivers, an electronic dc voltmeter connected temporarily between the agc bus and ground will serve as the tuning indicator. For most reliable operation, the receiver must be loosely coupled to the unknown-frequency signal source.

Except for communications receivers of older vintage, frequencies may be read directly from the tuning dial. The accuracy of a receiver employed as a frequency meter depends upon (1) accuracy of the original calibration, (2) freedom from drift, (3) readability of dial, and (4) resettability of dial. From 1% to 2% of indicated frequency would be considered excellent. Some communications receivers are equipped with a self-contained frequency spotter (e.g., a 100-kHz crystal oscillator) having harmonics to provide check points for periodic recalibration of the dial. With this refinement, the receiver can be recalibrated prior to each use as a frequency meter and can offer enhanced accuracy.

In the use of a superheterodyne receiver as a frequency meter, care must be taken to distinguish between images and real signals. The most satisfactory receiver for this application will, of course, be one having an excellent signal-to-image ratio. Care must also be taken against interfering signals from radio and tv stations (see Section 3.1F).

3.14 FIELD-STRENGTH METER

Like the radio receiver (Section 3.13), a frequency-calibrated field-strength meter also can be used as a continuously tunable, direct-reading radio-frequency meter; and, like the receiver, the field-strength meter employs a superheterodyne circuit for improved sensitivity and selectivity. Peak deflection of the self-contained microammeter of this instrument indicates exact tuning to a signal, and additionally this meter reads directly in volts, millivolts, and microvolts.

Conventional field-strength meters cover the ranges normally offered by general-coverage communications receivers, i.e., 500 kHz to 50 MHz, and some tune as low as 100 kHz. Accuracy is from ±1% to ±3% of indicated frequency. Some special field-strength meters cover television-channel frequencies only and are step-tuned, not continuously tunable.

Radio-frequency energy may be coupled into the field-strength meter via capacitance coupling, antenna pickup, or low-impedance transmission line. Some instruments make provision for all of these.

3.15 FREQUENCY SPOTTER

A *frequency spotter* is a single-frequency rf oscillator (usually of the crystal type) whose fundamental frequency is so chosen that its harmonics provide spot frequencies at convenient test points throughout a substantial portion of the radio-frequency spectrum. Thus, a 100-kHz oscillator may provide such check points every 100 kHz apart, from 100 kHz to 30 or 40 MHz. If the oscillator is closely stabilized, these spot frequencies are very reliable.

The spot frequencies may be monitored with a receiver (see Section 3.13), mixer (Section 3.6), heterodyne frequency meter (Section 3.7), or hf wave analyzer (Section 3.11). The fundamental frequencies commonly selected for frequency spotters are 50 kHz, 100 kHz, 1000 kHz, and 5 MHz. Some communications-type radio receivers are equipped with a self-contained 100-kHz crystal oscillator for frequency spotting.

The successive harmonics from a frequency spotter diminish in intensity. The highest spot frequency that has useful amplitude depends upon oscillator power output and the amount of intentional distortion in the signal. (A sine-wave signal has few harmonics, in a practical sense, and is of no value in this application.) In general, tube-type oscillators—since they operate at higher dc voltage than do transistor oscillators—give useful harmonics farther into the spectrum.

It should be noted that the frequency spotter is not itself a frequency-measuring device, but rather a generator of dependable signals which may be used as the standard-frequency (f_s) source in test setups. When operation of this device is closely stabilized to minimize frequency shift due to variations in voltage, temperature, humidity, and other parameters, the frequency spotter becomes a *frequency standard* and as such is discussed in the next chapter.

CHAPTER 4

FREQUENCY STANDARDS

This chapter describes representative frequency standards for radio frequencies and audio frequencies; these devices are sources of signals against which the calibration of other devices is checked. During the past 20 years, noteworthy progress has been made in frequency standardization methods, especially in the transition from time-honored crystal-type primary standards to the atomic type. Many new devices have appeared; so the survey here must necessarily be selective.

The distance we have traveled in frequency standardization is evident when it is noted that 50 years ago the absorption wavemeter was the accepted frequency-checking instrument, and for the standardization of this device the Bureau of Standards could say in its 1924 book *Radio Instruments and Measurements:* "The most direct method for the wave length calibration of a standard or commercial wavemeter is a comparison with a high-frequency alternator. From the speed of the machine and the number of poles or other structural data the frequency of alternation can be computed directly. The range of such alternators is, however, limited; the usual construction does not furnish a wave length shorter than 3000 meters."

The widespread need to measure frequency accurately is underlined by the fact that every type of electronics person, from the casual amateur to the sophisticated research engineer includes some sort of frequency standard among his essential equipment. The complexity of the standard is, of course, a function of the accuracy and stability required of it.

4.1 CLASSIFICATION OF STANDARDS

There are two classifications of standards of all kinds: *primary* and *secondary*. A *secondary standard is* one that derives its accuracy from having been calibrated against an even more dependable device, a *primary standard*. The primary standard is a device that needs no comparison with any other source based upon the same kind of units of measurement. Primary standards are noted for high precision and high stability. Primary standards usually are stationary; secondary standards may or may not be portable.

Secondary frequency standards are widely distributed and are usually found in laboratories, shops, stations, and schools. Primary standards, on the other hand, being costly and often bulky and usually requiring specialized professional attention, generally are found only in universities, government facilities, and advanced laboratories. Secondary standards are brought to them for calibration. Secondary standards often have lower long-term stability than primary standards do, being used primarily for relatively brief time intervals and subject to frequent recalibration against a primary standard. While it is true that some secondary frequency standards have elaborate provisions for temperature control and voltage control and may demonstrate long-term stability, they nevertheless remain in the category of secondary standards because they must be checked against a primary standard.

Whereas a secondary standard must be checked against a primary standard of the same sort (i.e., a secondary frequency standard must be checked against a primary frequency standard), a primary standard is checked against some fundamental physical quantity or may need no checking at all. Thus, a crystal-type primary standard may be checked against sidereal time; and the atomic-type primary standard, being controlled directly by the constant resonant frequency of certain atoms, needs no checking at all.

4.2 CRYSTAL-TYPE PRIMARY STANDARD

This device is based upon a highly precise quartz-crystal oscillator. High stability in this oscillator is obtained by employing a special low-drift quartz plate, closely regulating all operating voltages, closely controlling ambient temperature of the entire oscillator, controlling humidity, safeguarding against excessive vibration, and minimizing loading of the oscillator.

Fig. 4-1 shows a functional block diagram of this device. In this arrangement, the crystal oscillator (A) operates on 50 kHz and is followed by a buffer amplifier for isolation. The output of this stage contains harmonics 50 kilohertz apart far into the radio spectrum. The oscillator synchronizes a 10-kHz multivibrator and amplifier (B), and the output of this latter stage provides a 10,000-Hz signal with harmonics 10 kilohertz apart reasonably far into the radio spectrum. In succession follow synchronized multivibrator/amplifier stages for 1 kHz and 100 Hz (Stages C and D, respectively), which provide outputs of 1000 Hz and 100 Hz. From the diagram, it is seen that the multivibrators divide the oscillator frequency by 5 (Stage B), 50 (Stage C), and 500 (Stage D), each output having the same accuracy as that of the oscillator. The output of the 1000-Hz multivibrator/amplifier (C) drives a 1000-Hz synchronous clock. Any drift of the oscillator frequency may be detected when the time indicated by this clock is compared with standard time, and the oscillator frequency then is corrected (by means of fine tuning, adjusting of operating voltage and temperature, or all of these). Sidereal time can be measured with

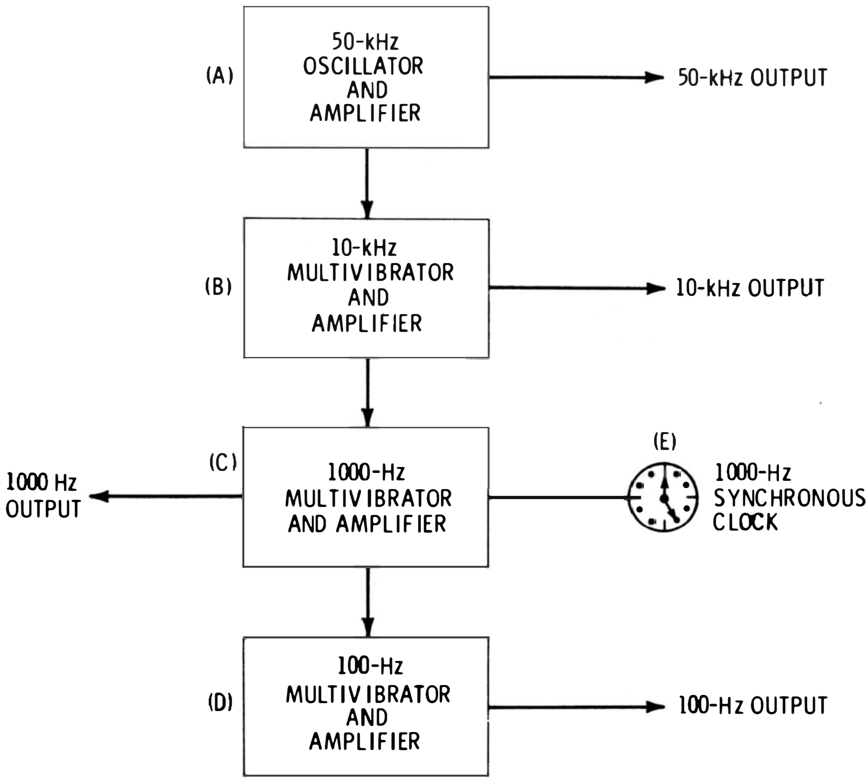


Fig. 4-1. Crystal-type primary standard.

great precision by using the methods of astronomy. The clock keeps correct time as long as the oscillator frequency is exactly 50 kHz (50,000 vibrations of the quartz plate are required for each second indicated by the clock); accordingly, frequency error may be determined in terms of the number of seconds by which the clock leads or lags correct time at the periodic checking instant. A frequency accuracy of the order of 1 part in 10 million, or better, is common for this type of primary standard.

There are variations of the scheme illustrated by Fig. 4-1. For instance, the system could start with a 100-kHz oscillator, and multivibrators can be provided at frequencies other than, or in addition to, those shown, to provide af, as well as rf checking frequencies.

Recent custom regards this device as a highly refined secondary standard, since it must be referred to an external quantity—standard time—for calibration. We retain the original classification here, however, since some of these devices are still in service in their original role, that of primary standards.

4.3 ATOMIC-TYPE PRIMARY STANDARD

Work with masers led to the discovery of natural resonance in atomic systems, such as a beam of cesium atoms, and to the epochal observation that this frequency is one of the most constant quantities in Nature. The phenomenon is explained by the fact that when stimulated particles fall to a lower energy level, they radiate energy of constant frequency (approximately 9192 MHz for cesium). The action is initiated by injecting microwave energy at the natural frequency of the atoms, to stimulate them. When the atoms fall back to a lower energy state, they radiate energy at their constant natural frequency. The next logical step was to utilize this phenomenon as a primary standard of frequency. With an atomic resonator as the basis, the result is a true *primary* standard, since no outside quantity need be referred to—the authority is self-contained, the atomic resonance of the atom.

Fig. 4-2 shows a functional block diagram of the essential arrangement of a cesium primary frequency standard (Hewlett-Packard Model 5061A). In this standard, the atomic resonator (A) embodies a cesium-beam tube in which cesium atoms travel through a microwave cavity. In the tube, the beam intensity is varied by a phase-modulated signal which sweeps through the atomic resonance frequency. This signal is generated by a 5-MHz crystal oscillator (J) and is phase-modulated, frequency-multiplied, and otherwise processed by G and E.

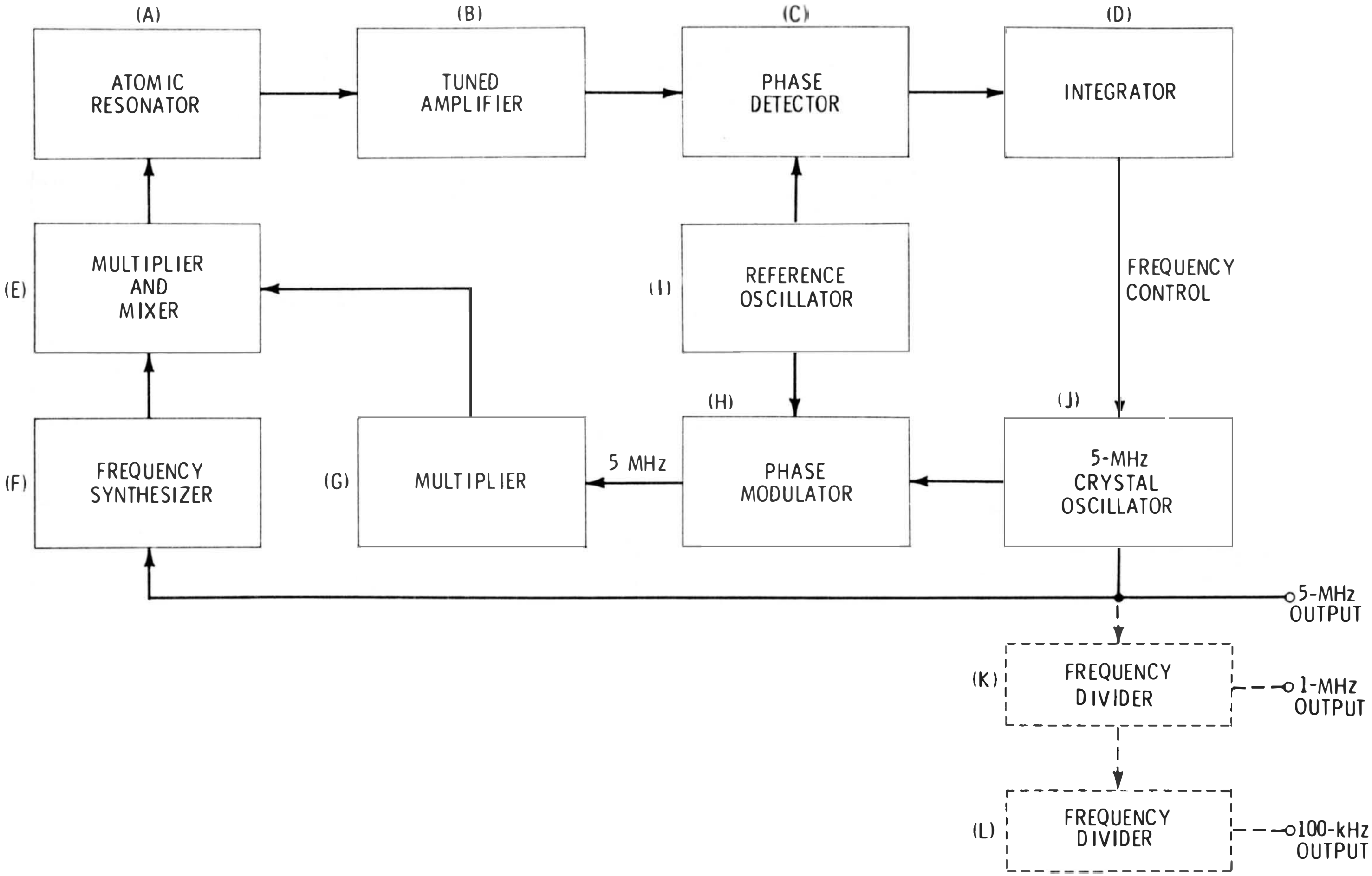


Fig. 4-2. Atomic-type frequency standard.

The output of the resonator is amplified (Stage B) and, through phase detector C and integrator D corrects the frequency of the crystal oscillator. This oscillator thus may be described as an atomic-resonator-controlled oscillator operated in a phase-locked system.

The crystal oscillator (J) supplies the 5-MHz output of the standard and may be applied to frequency dividers, such as K for 1 MHz and L for 100 kHz. A synchronous clock, operated from an atomic-type primary frequency standard, indicates correct time with high precision.

The accuracy of this standard is specified as $\pm 1 \times 10^{-11}$. The first cesium-beam frequency standard was introduced by Hewlett-Packard in 1964. The cesium unit is now accepted throughout the world as the definitive primary standard.

4.4 CRYSTAL-TYPE SECONDARY STANDARD

The *frequency spotter,* described in Section 3.15, Chapter 3, is the simplest form of secondary radio-frequency standard. It is also the commonest secondary standard. It is found in many versions, from simple to sophisticated, as complete units and also as components of other systems such as receivers, heterodyne frequency meters, and rf signal generators, and is supplied both in factory-built and kit types. This device usually is a fairly simple 100-kHz crystal oscillator.

Fig. 4-3 shows the circuit of a FET-type 100-kHz oscillator suitable for use as a secondary frequency standard. Here, the

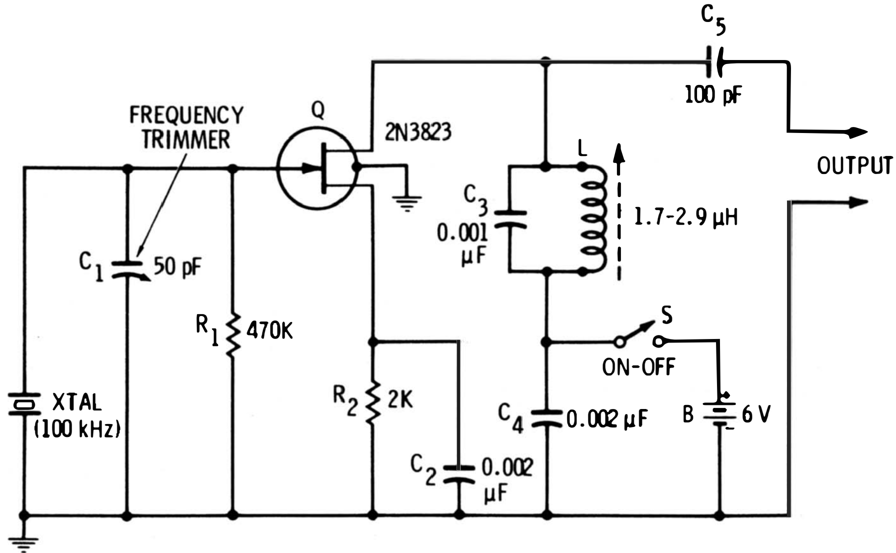
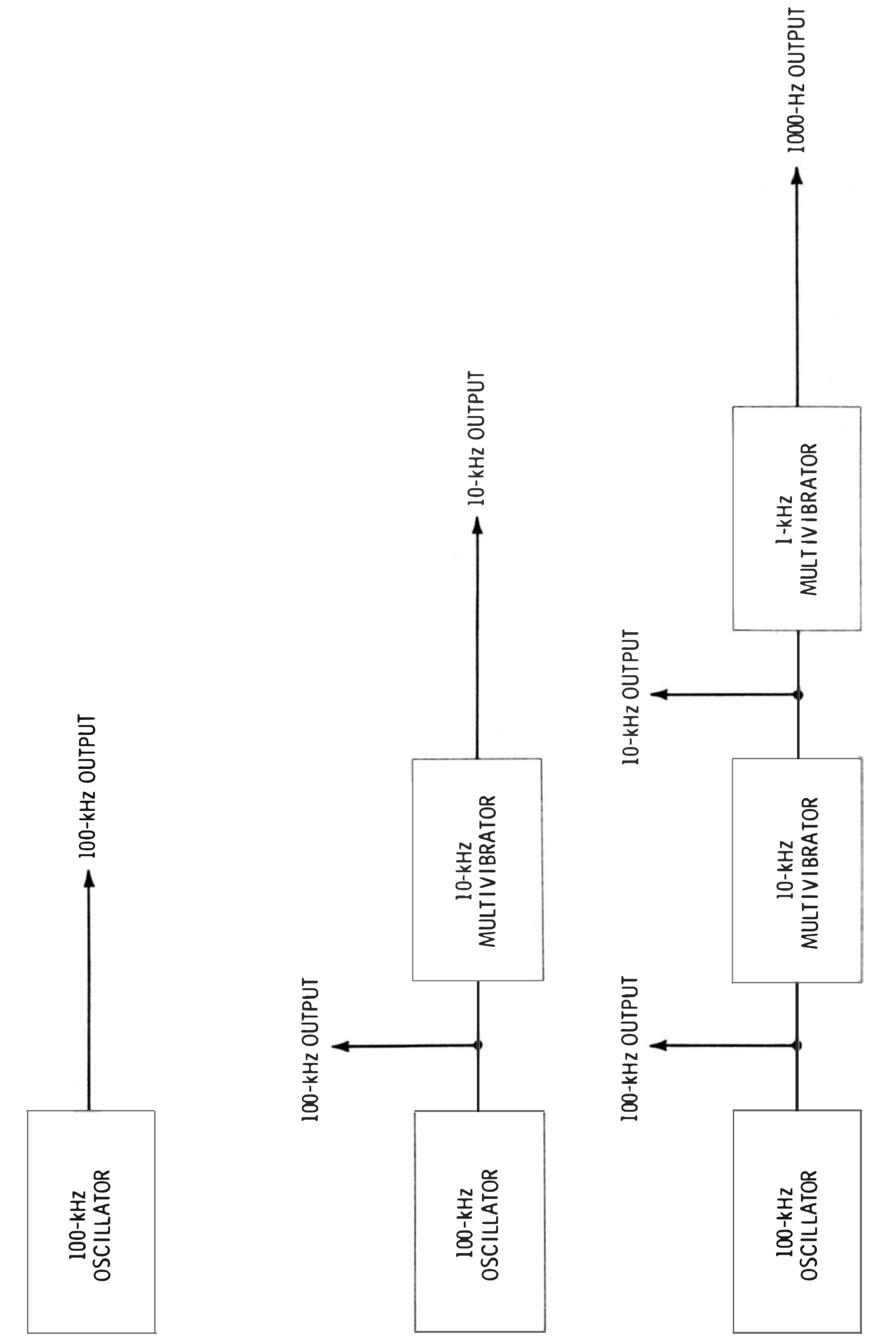


Fig. 4-3. 100-kHz crystal oscillator.



(A) Single crystal oscillator.

(B) Crystal oscillator and multivibrator.

(C) Crystal oscillator and two multivibrators.

Fig. 4-4. Secondary-standard layouts.

adjustable inductor (L) is slug-tuned for maximum output. Trimmer capacitor C_1 shifts the crystal frequency by a very small amount, allowing the oscillator to be adjusted against a primary standard. Similar circuits employ bipolar transistors, vacuum tubes, or ICs. While the 100-kHz frequency is popular, other standards employ 50 kHz, 1000 kHz, or 5 MHz.

Fig. 4-4 shows three common versions of the secondary standard. Fig. 4-4A is the single crystal oscillator described above. In Fig. 4-4B, a 10-kHz multivibrator has been added to provide 10,000-Hz output and harmonic check points. In Fig. 4-4C, 10-kHz and 1-kHz multivibrators both have been added to the oscillator to provide 10,000-Hz and 1000-Hz check points, respectively. Multivibrators at other frequencies also may be used. Each stage may be followed by a buffer amplifier for isolation and signal boosting, if desired. Also, a filter is sometimes connected in each external output when low-distortion outputs are desired on 100 kHz, 10 kHz, and 1 kHz.

The accuracy and stability of the crystal-type secondary standard depend upon (1) type of crystal, (2) temperature control, (3) operating-voltage regulation, and (4) recency of calibration. If a low-drift crystal is used without temperature control and voltage regulation, the frequency may be expected to be constant within 0.005% at ambient temperatures between zero and 50°C, following calibration by adjustment of C_1 (Fig. 4-3) for zero beat with a primary standard. Better performance may be expected when temperature and voltage are controlled.

4.5 ATOMIC-TYPE SECONDARY STANDARD

Like the primary standard described in Section 4.3, a secondary standard also can exploit the property of atomic resonance. The basic arrangement of an atomic-type secondary standard is essentially the same as that of the similar primary standard (see Fig. 4-2). In the secondary standard, however, rubidium vapor, rather than cesium, is employed as the atom source. Variations in the pressure of the buffer gas that is required with rubidium cause small variations in the atomic resonant frequency, and these necessitate that the instrument be checked periodically against a primary frequency standard. Hence, the rubidium-type unit is categorized as a secondary standard.

The rubidium secondary standard nevertheless offers superb stability and is superior to a stabilized, crystal-type secondary standard. Representative stability of the rubidium unit is $\pm 1 \times 10^{-11}$ per month.

4.6 SELF-EXCITED SECONDARY STANDARD

In unexacting measurements, a self-excited 50-kHz or 100-kHz oscillator sometimes will suffice as a secondary frequency standard. Most such oscillators have good stability at such low frequencies when they are solidly constructed, operated at low power, and lightly loaded.

Fig. 4-5 shows a bipolar-transistor-type, 100-kHz oscillator that can be used as a secondary frequency standard. The tuning slug of the 1.08- to 1.8-mH inductor (L_1) is adjusted for zero beat with a primary standard (usually a standard-frequency transmission picked up with a radio receiver). Similar oscillators may employ a field-effect transistor, integrated circuit, or vacuum tube.

The self-excited unit is reliable only during, or immediately after, calibration. Like all self-excited oscillators, this circuit is subject to an unpredictable amount of drift, as well as abrupt

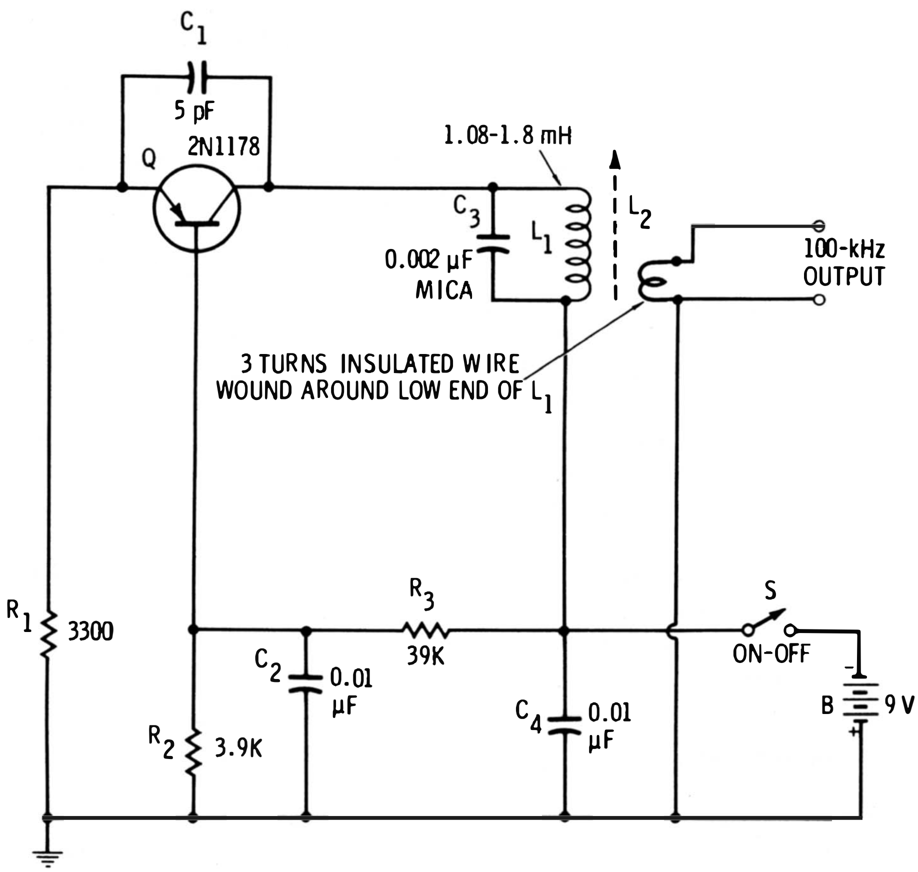


Fig. 4-5. Self-excited secondary standard.

frequency shifts that result from mechanical shock, body capacitance, and operating-voltage changes.

In the same light, a radio-frequency signal generator tuned to 50 kHz, 100 kHz, 1 MHz, or 5 MHz and precalibrated from a frequency standard makes a good self-excited secondary standard. Such a generator usually contains a low-drift circuit and often voltage regulation. As a secondary standard, the generator suffers, however, from low-voltage output. But a number of generators have an auxiliary 1-volt "high-output" terminal, and a signal of this amplitude is satisfactory for most frequency-standard uses. It should be noted, too, that the output of a good signal generator is a reasonably pure sine wave and accordingly lacks the harmonics that are so useful in using a frequency standard. However, the 1-volt output can be distorted by passing it through an external circuit containing a germanium diode biased into its most nonlinear region, and this will provide some harmonics.

4.7 STANDARD-FREQUENCY BROADCASTS

The National Bureau of Standards radio stations WWV (Colorado) and WWVH (Hawaii) transmit standard frequencies continuously day and night, and these signals may be used for the calibration of frequency standards and other equipment. WWV transmits on frequencies of 2.5, 5, 10, 15, 20, and 25 MHz; WWVH transmits on 2.5, 5, 10, 15, and 20 MHz. Both stations modulate all of their carriers with standard audio frequencies of 400, 500, and 600 Hz, each tone being maintained for 45 seconds. A 440-Hz tone is used at other intervals. The National Bureau of Standards also broadcasts a 60-kHz signal via Station WWVB (Colorado). The accuracy of the transmitted frequencies is maintained by a cesium-type primary standard (see Section 4.3) and is kept within ±2 parts in 100 billion.

For a full description of this service, see *NBS Special Publication 236, NBS Frequency and Time Broadcast Services* (25 cents, Superintendent of Documents, U. S. Government Printing Office, Washington, D.C. 20402).

4.8 RADIO STATIONS AS EMERGENCY STANDARDS

When no other source is available, a radio broadcast station can serve as an emergency frequency standard, since these stations are required to maintain their carrier frequencies within a few hertz. The procedure is to zero-beat the fundamental or a harmonic from the secondary standard under test (or other device) with the carrier of the station.

The greatest difficulty of this method is the inability to recognize zero beat accurately while the carrier is modulated with the station's program material. In the station's zeal to fill every second on the air, there is almost no break in music or talk. But, with patience, the operator will be rewarded (though infrequently) with a blank carrier.

4.9 AUDIO-FREQUENCY STANDARDS

Standards are available also for precise audio frequencies. These are discussed below.

A. Conventional frequency standard

Some of the frequency-divider stages of a primary or secondary radio-frequency standard deliver precise audio frequencies. Thus, in Fig. 4-1, 10 kHz, 1000 Hz, and 100 Hz are available; and in Fig. 4-4C, 10 kHz and 1000 Hz are available. Other audio frequencies may be obtained from either standard by means of suitable multivibrators with or without filters.

B. Low-frequency crystal oscillator

Special crystal oscillators are available down to 2000 Hz. These units have excellent frequency and drift characteristics. Typical frequency accuracy is ±100 ppm at 25°C; typical stability is ±0.005% from 0 to 50°C.

C. Tuning-fork oscillators

A tuning fork machined precisely for a desired frequency can be maintained in vibration by a transistor or tube circuit, and audio output may be picked up from the fork. The resulting oscillator can serve as an audio-frequency standard, especially if its temperature and operating voltage are closely stabilized.

Fig. 4-6 shows one version of the fork-controlled oscillator. Here, the driving coils (L_1 and L_2) and the pickup coils (L_3 and L_4) are wound on permanent magnets placed close to opposite tines of the fork. They do not touch the fork, so they do not cause mechanical restraint of the vibrations. Harmonic distortion is minimized by the filter and the degenerative network.

Commercial tuning-fork oscillators are available for frequencies from 1 Hz to 100 kHz, with an accuracy as good as 1 ppm. These units are compact, compared with some of the fork oscillators of past years that employed massive forks. The efficacy of modern subminiature tuning forks is evident from

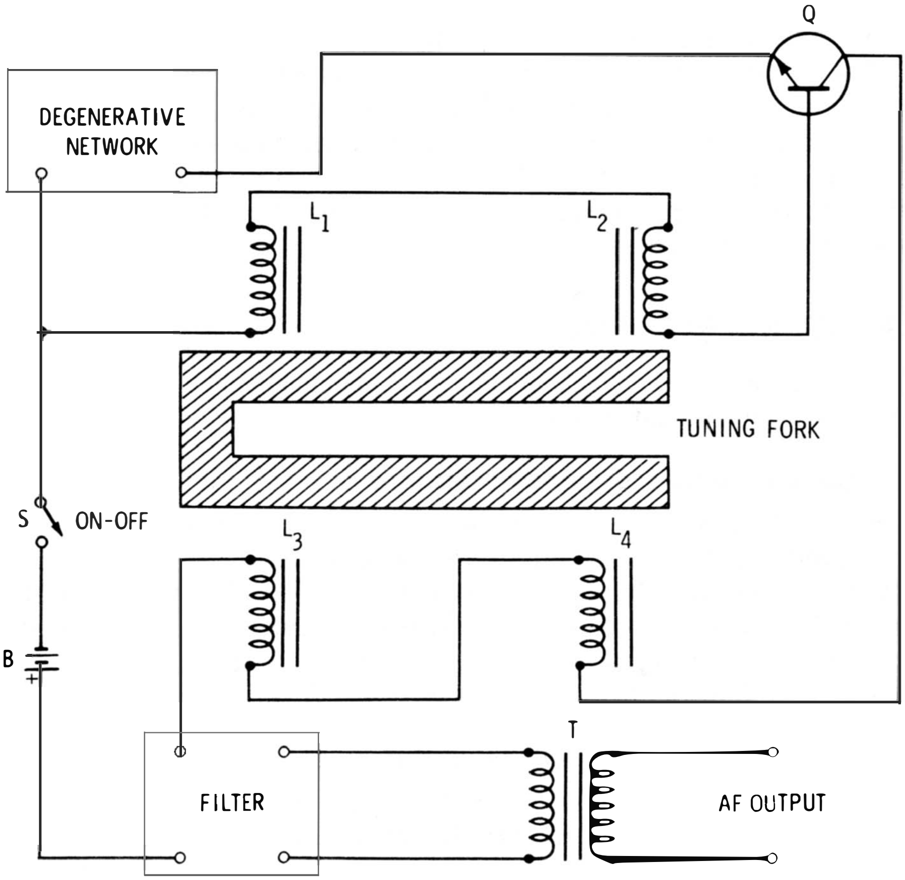


Fig. 4-6. Tuning-fork oscillator.

the performance of electronic watches driven by them; such a timepiece, actuated by a 1000-Hz fork, can show an error of only a minute or two per month.

D. Standard-frequency stations

As explained in Section 4.7, audio frequencies of 400, 440, 500, and 600 Hz are available as modulation on standard-frequency signals broadcast by the National Bureau of Standards on Stations WWV and WWVH. These signals have high accuracy.

These frequencies can also be heard via a telephone call to the National Bureau of Standards. Dial (303) 499-7111 (Boulder, Colorado).

E. Audio signal generator

A laboratory-type sine-wave audio signal generator providing discrete frequencies, rather than continuously variable tuning, is usable as a secondary audio-frequency standard, within its limitations of accuracy and drift. Such instruments can supply several thousand push-button-selected frequencies. The frequency span is typically 10 Hz to 1 MHz. Frequency accuracy is $\pm 0.2\%$, and frequency drift is of the order of 10 ppm/minute.

A good, continuously tunable audio signal generator, operated in conjunction with a digital-type audio-frequency meter (see Section 2.5, Chapter 2) to indicate the frequency, performs well as an audio-frequency standard. Here, the frequency accuracy is that of the digital counter. When in use, the generator can be regularly reset to correct any drift.

These sine-wave generators produce a very-low-distortion signal, so that no harmonics of useful amplitude are available. But, when the generator has square-wave as well as sine-wave output, the square wave will supply strong, odd-numbered harmonics.

APPENDIX A

FREQUENCY AND WAVELENGTH CONVERSION FACTORS

To Convert From	To	Multiply By
Centimeters	Meters	0.01
Centimeters	Millimeters	10
Cycles	Gigacycles	1×10^{-9}
Cycles	Kilocycles	0.001
Cycles	Megacycles	1×10^{-6}
Cycles	Teracycles	1×10^{-12}
Cycles/s	Gigacycles/s	1×10^{-9}
Cycles/s	Gigahertz	1×10^{-9}
Cycles/s	Hertz	1
Cycles/s	Kilocycles/s	0.001
Cycles/s	Kilohertz	0.001
Cycles/s	Megacycles/s	1×10^{-6}
Cycles/s	Megahertz	1×10^{-6}
Cycles/s	Teracycles/s	1×10^{-12}
Cycles/s	Terahertz	1×10^{-12}
Gigacycles	Cycles	1×10^{9}
Gigacycles	Kilocycles	1×10^{6}
Gigacycles	Megacycles	1000
Gigacycles	Teracycles	0.001
Gigacycles/s	Cycles/s	1×10^{9}
Gigacycles/s	Gigahertz	1
Gigacycles/s	Hertz	1×10^{9}
Gigacycles/s	Kilocycles/s	1×10^{6}

To Convert From	To	Multiply By
Gigacycles/s	Kilohertz	1×10^{6}
Gigacycles/s	Megacycles/s	1000
Gigacycles/s	Megahertz	1000
Gigacycles/s	Teracycles/s	0.001
Gigacycles/s	Terahertz	0.001
Gigahertz	Cycles/s	1×10^{9}
Gigahertz	Gigacycles/s	1
Gigahertz	Hertz	1×10^{9}
Gigahertz	Kilocycles/s	1×10^{6}
Gigahertz	Kilohertz	1×10^{6}
Gigahertz	Megacycles/s	1000
Gigahertz	Megahertz	1000
Gigahertz	Teracycles/s	0.001
Gigahertz	Terahertz	0.001
Hertz	Cycles/s	1
Hertz	Gigacycles/s	1×10^{-9}
Hertz	Gigahertz	1×10^{-9}
Hertz	Kilocycles/s	0.001
Hertz	Kilohertz	0.001
Hertz	Megacycles/s	1×10^{-6}
Hertz	Megahertz	1×10^{-6}
Hertz	Teracycles/s	1×10^{-12}
Hertz	Terahertz	1×10^{-12}
Kilocycles	Cycles	1000
Kilocycles	Gigacycles	1×10^{-6}
Kilocycles	Megacycles	0.001
Kilocycles	Teracycles	1×10^{-9}
Kilocycles/s	Cycles/s	1000
Kilocycles/s	Gigacycles/s	1×10^{-6}
Kilocycles/s	Gigahertz	1×10^{-6}
Kilocycles/s	Hertz	1000
Kilocycles/s	Kilohertz	1
Kilocycles/s	Megacycles/s	0.001
Kilocycles/s	Megahertz	0.001
Kilocycles/s	Teracycles/s	1×10^{-9}
Kilocycles/s	Terahertz	1×10^{-9}
Kilohertz	Cycles/s	1000
Kilohertz	Gigacycles/s	1×10^{-6}
Kilohertz	Gigahertz	1×10^{-6}
Kilohertz	Hertz	1000
Kilohertz	Kilocycles/s	1
Kilohertz	Megacycles/s	0.001
Kilohertz	Megahertz	0.001
Kilohertz	Teracycles/s	1×10^{-9}
Kilohertz	Terahertz	1×10^{-9}
Megacycles	Cycles	1×10^{6}
Megacycles	Gigacycles	0.001

To Convert From	To	Multiply By
Megacycles	Kilocycles	1000
Megacycles	Teracycles	1×10^{-6}
Megacycles/s	Cycles/s	1×10^{6}
Megacycles/s	Gigacycles/s	0.001
Megacycles/s	Gigahertz	0.001
Megacycles/s	Hertz	1×10^{6}
Megacycles/s	Kilocycles/s	1000
Megacycles/s	Kilohertz	1000
Megacycles/s	Megahertz	1
Megacycles/s	Teracycles/s	1×10^{-6}
Megacycles/s	Terahertz	1×10^{-6}
Megahertz	Cycles/s	1×10^{6}
Megahertz	Gigacycles/s	0.001
Megahertz	Gigahertz	0.001
Megahertz	Hertz	1×10^{6}
Megahertz	Kilocycles/s	1000
Megahertz	Kilohertz	1000
Megahertz	Megacycles/s	1
Megahertz	Teracycles/s	1×10^{-6}
Megahertz	Terahertz	1×10^{-6}
Meters	Centimeters	100
Meters	Millimeters	1000
Millimeters	Centimeters	0.1
Millimeters	Meters	0.001
Teracycles	Cycles	1×10^{12}
Teracycles	Gigacycles	1000
Teracycles	Kilocycles	1×10^{9}
Teracycles	Megacycles	1×10^{6}
Teracycles/s	Cycles/s	1×10^{12}
Teracycles/s	Gigacycles/s	1000
Teracycles/s	Gigahertz	1000
Teracycles/s	Hertz	1×10^{12}
Teracycles/s	Kilocycles/s	1×10^{9}
Teracycles/s	Kilohertz	1×10^{9}
Teracycles/s	Megacycles/s	1×10^{6}
Teracycles/s	Megahertz	1×10^{6}
Teracycles/s	Terahertz	1
Terahertz	Cycles/s	1×10^{12}
Terahertz	Gigacycles/s	1000
Terahertz	Gigahertz	1000
Terahertz	Hertz	1×10^{12}
Terahertz	Kilocycles/s	1×10^{9}
Terahertz	Kilohertz	1×10^{9}
Terahertz	Megacycles/s	1×10^{6}
Terahertz	Megahertz	1×10^{6}
Terahertz	Teracycles/s	1

APPENDIX B

FREQUENCY-WAVELENGTH FORMULAS

f in Hz. $\lambda = \frac{3 \times 10^8}{f}$ m $= \frac{3 \times 10^{10}}{f}$ cm $= \frac{3 \times 10^{11}}{f}$ mm

f in kHz. $\lambda = \frac{300,000}{f}$ m $= \frac{3 \times 10^7}{f}$ cm $= \frac{3 \times 10^8}{f}$ mm

f in MHz. $\lambda = \frac{300}{f}$ m $= \frac{30,000}{f}$ cm $= \frac{300,000}{f}$ mm

f in GHz. $\lambda = \frac{0.3}{f}$ m $= \frac{30}{f}$ cm $= \frac{300}{f}$ mm

f in THz. $\lambda = \frac{0.0003}{f}$ m $= \frac{0.03}{f}$ cm $= \frac{0.3}{f}$ mm

λ in m. f $= \frac{3 \times 10^8}{\lambda}$ Hz $= \frac{300,000}{\lambda}$ kHz $= \frac{300}{\lambda}$ MHz

$= \frac{0.3}{\lambda}$ GHz $= \frac{0.0003}{\lambda}$ THz

λ in cm. f $= \frac{3 \times 10^{10}}{\lambda}$ Hz $= \frac{3 \times 10^7}{\lambda}$ kHz $= \frac{30,000}{\lambda}$ MHz

$= \frac{30}{\lambda}$ GHz $= \frac{0.03}{\lambda}$ THz

λ in mm. f $= \frac{3 \times 10^{11}}{\lambda}$ Hz $= \frac{3 \times 10^8}{\lambda}$ kHz $= \frac{300,000}{\lambda}$ MHz

$= \frac{300}{\lambda}$ GHz $= \frac{0.3}{\lambda}$ THz

APPENDIX C

FREQUENCY-PERIOD FORMULAS

f in Hz. $t = \frac{1}{f}\,s = \frac{1000}{f}\,ms = \frac{10^6}{f}\,\mu s$

f in kHz. $t = \frac{0.001}{f}\,s = \frac{1}{f}\,ms = \frac{1000}{f}\,\mu s$

f in MHz. $t = \frac{10^{-6}}{f}\,s = \frac{0.001}{f}\,ms = \frac{1}{f}\,\mu s$

f in GHz. $t = \frac{10^{-9}}{f}\,s = \frac{10^{-6}}{f}\,ms = \frac{0.001}{f}\,\mu s$

f in THz. $t = \frac{10^{-12}}{f}\,s = \frac{10^{-9}}{f}\,ms = \frac{10^{-6}}{f}\,\mu s$

t in s. $f = \frac{1}{t}\,Hz = \frac{0.001}{t}\,kHz = \frac{10^{-6}}{t}\,MHz$

$= \frac{10^{-9}}{t}\,GHz = \frac{10^{-12}}{t}\,THz$

t in ms. $f = \frac{1000}{t}\,Hz = \frac{1}{t}\,kHz = \frac{0.001}{t}\,MHz$

$= \frac{10^{-6}}{t}\,GHz = \frac{10^{-9}}{t}\,THz$

t in μs. $f = \frac{10^6}{t}\,Hz = \frac{1000}{t}\,kHz = \frac{1}{t}\,MHz$

$= \frac{0.001}{t}\,GHz = \frac{10^{-6}}{t}\,THz$

APPENDIX D

ABBREVIATIONS USED IN THIS BOOK

af—Audio frequency
agc—Automatic gain control
a-m—Amplitude modulation, amplitude modulated
AMP—Amplifier

C—Capacitance, capacitor
cm—Centimeter (s)
coax—Coaxial (line or cable)
COM—Common
cps—Cycle (s) per second

D—Diode
d—Distance
dc—Direct current
DET—Detector
div—Division

E—Voltage
e.g.—For example

F—Farad (s)
f—Frequency
f_c—Carrier frequency
FET—Field-effect transistor
fm—Frequency modulation, frequency modulated
f_s—Standard frequency
ft—Foot, feet
f_x—Unknown frequency

GEN—Generator
GHz—Gigahertz
GND—Ground

H—Henry (s)
hf—High frequency
Hz—Hertz

IC—Integrated circuit
i.e.—That is,
i-f—Intermediate frequency
ir—Infrared

K—Kilohms, × 1000
kHz—Kilohertz

L—Inductance, inductor
LC—Inductance-capacitance combination

LCR—Inductance-capacitance-resistance combination
lf—Low frequency

M—Magnet, meter (instrument
m—Meter(s) (unit of measurement)
MΩ—Megohm(s)
mf—Medium frequency
mH—Millihenry(s)
MHz—Megahertz
mm—Millimeter(s)
mod—Modulation, modulated
ms—Millisecond(s)
mV—Millivolt(s)

n—Number, a multiple
NBS—National Bureau of Standards
NC—No connection
ns—nanosecond(s)

pF—Picofarad(s)
ppm—Part(s) per million
prf—Pulse-repetition frequency
prr—Pulse-repetition rate

Q—Figure of merit ($Q = X/R$), symbol for transistor

R—Resistance, resistor
RC—Resistance-capacitance combination
rf—Radio frequency

RL—Resistance-inductance combination
rms—Root mean square

S—Switch, signal strength (as in *S meter*)
s—Second(s)
shf—Superhigh frequency
spdt—Single-pole double-throw
SYNC—Synchronization, synchronizing

T—Transformer
t—Period
THz—Terahertz
tv—Television
tvm—Transistorized voltmeter

uhf—Ultrahigh frequency
uv—Ultraviolet

V—Volt(s), vane
v—Velocity of light (300,000,000 meters/second)
VA—Volt-ampere(s)
vhf—Very-high frequency
vlf—Very-low frequency
vtvm—Vacuum-tube voltmeter

W—Watt(s)
ww—Wirewound

XTAL—Crystal

GREEK LETTERS

μA—Microampere(s)
μF—Microfarad(s)
μH—Microhenry(s)
μs—Microsecond(s)
λ—Wavelength
θ—Phase angle
π—3.1416

Index

T

U

V

W

X

Z

FREQUENCY and Its MEASUREMENT

by Rufus P. Turner

This book is addressed to the reader who knows practical electronics and who desires more information about frequency and frequency measurement than what is provided by the average electronics textbook. It gives a brief introduction to frequency and several methods of frequency measurement.

Chapter 2 covers audio-frequency measurement. Some of the methods covered are the beat-note method, induction-type frequency meter, reed-type frequency meter, and analog and digital frequency meters.

Radio-frequency measurement is covered in Chapter 3. Special precautions such as lead length, grounding, bypassing, shielding, and harmonics are discussed. Some of the instruments covered include wavemeters, Lecher frame, slotted line, dip meter, and Lissajous figures.

It is hoped that *Frequency and Its Measurement* will help the technician to select a suitable method for his particular frequency measurement problem.

Rufus Turner is no stranger to readers of technical literature. A prolific writer, he has over 2500 magazine articles and more than 40 books to his credit. He earned his B.A. degree (with honors) at California State University at Los Angeles, and his M.A. and Ph.D. degrees at the University of Southern California. He is licensed as a registered professional engineer in California and has had experience both in engineering and college teaching. Some of the other books by Dr. Turner are *abc's of Calculus, abc's of Electronic Power, abc's of FET's, abc's of Integrated Circuits, abc's of Resistance and Resistors, abc's of Thermistors, abc's of Voltage-Dependent Resistors, abc's of Zener Diodes, FET Circuits, Metrics for the Millions, Solar Cells and Photocells, Solid-State Components,* and *Technical Writer's and Editor's Stylebook,* all published by Howard W. Sams & Co., Inc.

HOWARD W. SAMS & CO., INC.
THE BOBBS-MERRILL CO., INC.