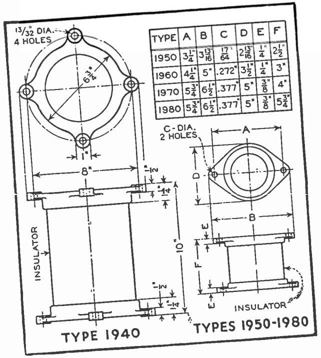

TYPE	A	B	C	D	E	F
1950	$3\frac{1}{4}$"	$3\frac{13}{16}$"	$\frac{17}{64}$"	$2\frac{13}{16}$"	$\frac{1}{4}$"	$2\frac{1}{2}$"
1960	$4\frac{1}{4}$"	5"	.272"	$3\frac{1}{2}$"	$\frac{1}{4}$"	3"
1970	$5\frac{3}{4}$"	$6\frac{1}{2}$"	.377"	5"	$\frac{3}{8}$"	4"
1980	$5\frac{3}{4}$"	$6\frac{1}{2}$"	.377"	5"	$\frac{3}{8}$"	$5\frac{3}{4}$"

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H. F. Frequency Measurements

PART I

By the Engineering Department, Aerovox Corporation

WAR-TIME interest in *very high, ultra high,* and *super high* frequencies, both in the armed services and in civilian defense, has directed special attention toward the subject of frequency measurements in these regions. This is partly because the familiar guide posts, such as the highly accurate standard-frequency reference signals and their harmonics, so widely used in lower-frequency measurements, are notably absent from the microwave spectrum.

Because of the limited communication range of most of the extremely high frequency systems now being developed, it becomes impracticable to transmit standard-frequency signals over an appreciable service area. Thus: the burden of standardization and measurement rests with the individual maker of high-frequency measurements in all cases except those instances in which the useful range of present standard-frequency instruments may be extended, or in which auxiliary secondary standards may be referred to lower-frequency standards.

While the technique employed in measuring the extremely high frequencies does not differ greatly from that employed at lower frequencies, certain modifications of apparatus are required in most cases, and, in general, special procedures are necessary to minimize errors in the former case. It is the purpose of these articles to review, from an academic standpoint, the several methods of frequency measurement especially applicable to the region between 30 Mc. and 30,000 Mc., to explain how the utility of existing lower-frequency standard-signal equipment may be extended to permit extremely high frequency measurements, and to describe several special systems and devices which are specifically for use in the region 30-30,000 Mc.

The sequence of topics will follow the conventional manner of development, progressing from rudimentary resonant-circuit devices through more complicated systems and methods which make use of generated signals or beat note methods. A representative member of each topic group has been chosen for illustration in all cases, except where distinct variations in type offer obvious individual advantages.

The art of frequency measurement *per se* had its beginnings in simple measuring or standardizing devices based upon the resonance phenomenon or the ability to measure *wavelength* with simple implements. Extremely high frequency measurements, as well, may be made in the simplest fashion by means of these rudimentary methods. At the same time, some of these methods lend themselves even more readily to microwave measurements because of the small physical size of a single wavelength at the extremely high frequencies. Our survey of the art consequently begins with a review of wavemeters and Lecher wire systems.

WAVE METERS

The simple absorption wavemeter may readily be adapted to frequency measurements in the very high, ultra high, and super high regions by reducing the values of its normal induc-

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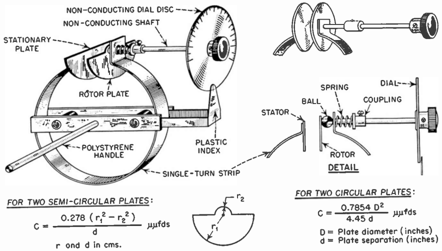

FOR TWO SEMI-CIRCULAR PLATES:

$$C = \frac{0.278\,(r_1^2 - r_2^2)}{d}\ \mu\mu\text{fds}$$

r and d in cms.

FOR TWO CIRCULAR PLATES:

$$C = \frac{0.7854\,D^2}{4.45\,d}\ \mu\mu\text{fds}$$

D = Plate diameter (inches)
d = Plate separation (inches)

Figure 1

tance and capacitance elements to resonate in these regions. The instrument is then operated in the conventional manner to check the frequency of microwave transmitters, receivers, and oscillators.

In most cases, reduction of inductance will resolve into a simpler mechanical task than will reduction of capacitance. It is much easier by comparison to reduce the size of a coil, either by decreasing the number of its turns, reducing the coil diameter, increasing coil length for a given number of turns, or by some combination of these measures. The variable condenser, adjustable element of the absorption wavemeter, may be reduced in capacitance only by removal of plates from its assembly, reducing plate area, increasing plate separation, or by a combination of these measures.

In some cases, when only one rotor and one stator plate remain in the unit, the maximum capacitance may still be excessive for some frequencies, and it may become necessary to space the two plates considerably or to cut away a portion of one or both to reduce the active area.

The highest frequency which may be attained by an absorption wavemeter tuned by such a small condenser is determined by the minimum capacitance of the latter. In variable condensers with low values of maximum capacitance, the minimum value becomes largely a function of the mounting hardware and rotor shaft, as well as the unmeshed-plate capacitance, and this minimum will often be sufficiently high with respect to the maximum capacitance to constrict the wavemeter tuning range. This condition will entail a redesign of the entire condenser to include a diminutive rotor shaft together with reduction in size, or complete elimination of stator mounting hardware.

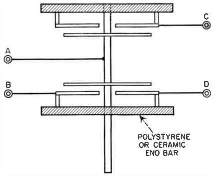

Figure 2

The dimensions for wavemeter components may be determined by means of the following formulae:

(1) $$f = \frac{1{,}000{,}000}{6.28\sqrt{LC}}\ \text{kilocycles}$$

(2) $$L = \frac{1{,}000{,}000}{39.49\,f^2 C}\ \text{microhenries}$$

(3) $$C = \frac{1{,}000{,}000}{39.49\,f^2 L}\ \text{micromicrofarads}$$

(4) $$L = \frac{0.2\,D^2 N^2}{3D + 9l}\ \text{microhenries}$$

In each of which:

L is inductance of coil (μh)
C is capacitance of condenser ($\mu\mu$fd)
D is diameter of single-layer coil (inches)
l is length of single-layer coil (inches)
N is number of turns in single-layer coil

Where extremely high frequencies are to be measured over the widest possible frequency range, the variable condenser may be made a part of a rigid single-turn coil, as shown in Figure 1, in order to eliminate all of the usual structural components. There are many possible variations of this design which will suggest themselves to the reader.

In some cases, a satisfactory wavemeter condenser may be constructed from a small split-stator unit, cut down from a larger condenser, as shown in Figure 2, to include as few as one rotor and one stator plate per section. The two separate stator sections are insulated from each other by mounting upon separate end plates or end bars of high-grade insulating material, such as a ceramic or polystyrene. Two pairs of diminutive coil terminals are provided. When the coil is plugged into terminals A-B, one section of this condenser is employed for tuning; but when it is plugged into terminals C-D, the two sections are connected automatically in series across the coil, yielding a maximum capacitance equal to one-half that of a single section. The same coil may thus be employed to cover two frequency bands; the lowest one with the single section, and the highest with the two sections in series.

In all high-frequency wavemeter applications, distributed and body capacitances are of tremendous importance, and every means must be enlisted to minimize the effects of both. For this reason, self-supporting coils with large turn-spacing, and open-type instrument construction devoid of all metallic casing and hardware are recommended. A simple self-supporting assembly of coil and condenser is ideal. Likewise, the tuning shaft should be a long rod of high-quality, non-hygroscopic insulating material, a long handle of similar material must be provided for holding the instrument in order to eliminate body-capacitance effects, and the dial plate must be made of non-conducting material. These constructional features are exemplified by the design in Figure 1.

Indicators, such as flashlamps, neon lamps, indicating meters, and the like, are not recommended for connection into high-frequency wavemeter circuits, since they tend to introduce large amounts of stray capacitance. In lieu of direct indication in the resonant circuit, satisfactory wavemeter indications may be obtained within the circuit under measurement, as for example by observation of a grid- or plate-circuit milliammeter in a high-frequency transmitter stage or of blocking action in a receiver under test, as the wavemeter is tuned through resonance. In general, these indications within the tested circuit will prove more sensitive than those obtained with indicating devices connected directly to the wavemeter, since the latter tend to load the wavemeter rather heavily and obscure its exact resonant point.

In a number of cases, high-frequency measurements by means of resonant circuits, as by the absorption wavemeter method, will require very small inductance values. This applies likewise to frequency-determining oscillator circuits. When inductors are reduced to short, straight lengths of wire, rather than the usual coils, the following formula (from Bureau of Standards Circular C74) will be of aid in determining the inductance value:

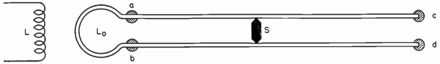

Figure 3

(6)

$$L = 0.002\,l\left[2.303\,\log_{10}\frac{4l}{d} - 0.75\right]\ \text{micro-henries}$$

Where
l = length of straight wire (cms)
d = diameter of wire (cms.)

The term $2l/d$ should be added inside the brackets when l is less than 1000 d

If natural, rather than common logarithms are employed, the multiplier 2.303 may be eliminated

LECHER WIRES

By means of Lecher wires, high frequencies may be determined by means of ordinary linear measurements of wavelength. This system ranks with the absorption wavemeter in simplicity and is somewhat more convenient for most of the extremely high frequencies since it requires no elaborate calibration against frequency standards, the standard of measurement being merely an accurately-graduated ruler or meter stick.

In Lecher wire systems, metric or English length measurements are made, as will be shown presently, between successive half-wave points along the wires which are coupled to the high-frequency transmitter, receiver, or oscillator. Because of the short wavelengths which correspond to the extremely high frequencies, the Lecher wire system is particularly suitable for measurements in the microwave spectrum, since the wire system will occupy the small space commonly occupied by other radio instruments.

A practical Lecher wire system is shown in Figure 3. A single, non-ferrous, solid wire is bent to form a coupling loop L_o, and the two parallel lines formed by the leads to the loop are stretched taut between the stand-off insulators, a, b, c, and d. S is a metallic short-circuiting bridge arranged to slide along the parallel wires. In some Lecher wire systems, the parallel conductors take the form of heavy brass or copper rods, and the short-circuiting bridge is a solid metallic block with clearance holes for the rods. Gripping spring blades are mounted within the sliding block, pressing tightly against the rods.

The parallel wire or rod section must be at least one wave-length long at the lowest frequency to be measured. (The wave-length in inches may be determined by dividing 1,181,100 by the frequency in megacycles). The loop L_o is coupled to the tank coil, L, of the high-frequency transmitter, receiver, or oscillator under test. The short-circuiting bridge is then slid along the parallel wires until an indication is obtained in the circuit under test. If the latter is within a transmitter or oscillator, this indication will be a sharp change in the deflection of the DC milliammeter in the grid or plate circuit. If it is a receiver, adjusted to a slightly oscillating state, the indication will be in the form of a sudden blocking action or "plop" denoting stoppage of oscillation.

The bridge is then moved farther along in the same direction until another such point is located. (If loose coupling is provided between the Lecher wire system and the apparatus under test, these points will be quite sharp). The distance (l) measured between these two points will be exactly one-half wavelength, from which the unknown frequency may be determined:

(7) $$F_{Mc} = \frac{150}{l}\ \text{when } l \text{ is measured in meters}$$

(8) $$F_{Mc} = \frac{5906}{l}\ \text{when } l \text{ is measured in inches}$$

Wavelength in meters may be measured within 1 millimeter with a standard meter stick, to obtain an accuracy of 20% at 30,000 Mc., 2% at 3000 Mc., 0.2% at 300 Mc., or 0.02% at 30 Mc. Wavelengths may be measured in inches within $\frac{1}{32}$ inch with a good-grade ruler, yardstick or scale, to obtain an accuracy of 15.8% at 30,000 Mc., 1.58% at 3000 Mc., 0.158% at 300 Mc., or 0.0158% at 30 Mc.

In order to function properly, Lecher wires must be mounted as nearly in the clear as possible. For this reason, attachment is made only to small stand-off insulators at each end, no intermediate supports being employed. The short-circuiting bridge is preferably of small cross sectional area and must make firm contact with the parallel wires or rods with which it must maintain a true perpendicular relation at all settings.

For maximum sharpness of response, the loosest practicable coupling for readable indication must be employed. And while it is entirely feasible to utilize an indicating device, such as a thermogalvanometer or low-current flashlamp, sliding in contact with the parallel wires as a direct-indicating short-circuiting bridge, sharpest indications will be obtained when the response points are detected instead within the circuit under test.

Oscillators, wavemeters, transmitters, and receivers, as well as many other extremely high-frequency circuits and devices may be calibrated directly from Lecher wires when the accuracy provided by this system is consistent with requirements.

In practice, the small Lecher wire systems required for extremely high-frequency testing are generally constructed of no. 12 or no. 14 bare copper wire spaced at a distance of approximately 2 inches and supported at each end by the smallest ceramic or polystyrene stand-off insulators or support pillars mounted on a base-board of good-quality insulating material. The short-circuiting bridge is usually constructed of heavy brass or copper bar stock with knife edges for good contact, and often carries an index pointer which travels along a centimeter or inch scale made of non-conducting material and mounted alongside or below the wires. The bridge is moved along the wires by means of a handle or high-quality, non-hygroscopic insulating material, often in the form of a long rod.

The Lecher wire principle is the basis of a simple but effective "trombone" wavemeter, shown in Figure 4, which is tuned by moving a sliding section (l_2) in and out of a stationary section (l_1). Although free to move, the sliding section fits sufficiently tight within the stationary section to provide good electrical contact at all settings. The coupling loop is formed by the end bend of the stationary section, while the short circuiting bridge is formed by the end bend of the movable section. A long handle of high-quality insulating material is attached to this latter bend. The slide may also carry an index pointer to travel along an inch or centimeter scale, mounted as shown in the drawing.

The two sections of the trombone wavemeter may be made of telescoping brass or copper tubing for both members, or of tubing for the stationary section with rod stock for the slide.

For maximum tuning range, the length of the two sections will be equal. The total length of the two sections must equal at least one wavelength at the lowest frequency to be measured.

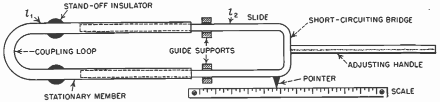

Figure 4