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ESTABLISHMENT OF RADIO STANDARDS OF FREQUENCY BY THE USE OF A HARMONIC AMPLIFIER

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ABSTRACT

A method is described for measuring the ratio of a radio to an audio-frequency by the use of a harmonic amplifier. The harmonic amplifier makes it possible to use harmonics of a very high order from a known low-frequency source, such as a standard tuning fork. The method consists essentially of the production of harmonics of the fundamental frequency of an alternating current by means of the nonlinear characteristics of electron tubes, the selection of any desired harmonic by means of tuned circuits, and its amplification to sufficient power to operate a standard frequency meter (wave meter). Any harmonic of the source may be selected, and thus from a known audio-frequency source a frequency meter may be standardized throughout its entire range.

The harmonic amplifier consists of two units, one having a range from 8 to 450 kc, the other from 400 to 4,000 kc. The first unit supplies a harmonic which is used as the fundamental for the second unit. The harmonic amplifier is given a preliminary calibration, so that the harmonic multiples can be readily determined.

A fixed frequency generator, such as a piezo oscillator, may be standardized with the aid of an auxiliary device to determine the frequency of the beat note occurring between a harmonic of the amplifier and the fixed frequency. The device used for this purpose is a sonometer. It consists of a steel piano wire mounted horizontally across two movable knife-edges with a known tension applied. The beat-note frequency is applied to the wire through a telephone receiver. The wire vibrates when its frequency is equal to the applied frequency. The frequency of vibration may be computed from the length, tension, and mass per unit length of the wire. Two audio-frequencies may be compared very accurately by the use of the harmonic amplifier and sonometer.

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I. INTRODUCTION

In the establishment of standards of radio-frequency several methods have been used by the Bureau of Standards.[1] The harmonics from an electrically driven standard tuning fork give accurate frequency points and have been used by various laboratories. A very complete arrangement for obtaining and using harmonics from a tuning fork is maintained by the Bell Telephone Laboratories (Inc.), and has been described by them.[2] The method here described is similar to and was suggested by that system. It is simpler, however, and has been adapted to the needs of this laboratory and has proved to be a very satisfactory method of frequency standardization.

The method consists, essentially, of the production of harmonics from a fundamental frequency source by means of the nonlinear characteristics of electron tubes, the selection of desired harmonics by means of tuned circuits, and the amplification of a desired harmonic to sufficient power to operate a standard frequency meter (wave meter). Any harmonic of the source may be selected, and thus from a known audio-frequency source a frequency meter may be standardized throughout its entire range. Any fixed frequency generator, such as a piezo oscillator, may be standardized with the aid of an auxiliary device to determine the frequency of the audio beat between a harmonic of the amplifier and the fixed frequency.

II. DESCRIPTION OF METHOD

The harmonic amplifier consists of two units, one for the production, selection, and amplification of the harmonics of frequencies from 8 to 450 kc and the other for the higher harmonics covering a range from 400 to 4,000 kc. The first unit supplies a harmonic which is used as the fundamental for the second unit. The frequency meter is coupled directly to the last stage of the amplifier, and the amplification is such that sufficient power is obtained so that the resonance indicator of the frequency meter may be used directly; that is, as it is normally used in frequency measuring work. The harmonic amplifier may be used with any low-frequency source as a basic standard. A 1,004-cycle standard tuning fork was used as the fundamental frequency source in the greater part of this frequency standardization. A 100-cycle fork was used to give a larger number of points below

[1] A general summary of the various methods is given in the article "Reducing the guesswork in tuning," J. H. Dellinger, Radio Broadcast, **3**, p. 241; July, 1923. See also "A method of measuring very short radio wave lengths and their use in frequency standardization," F. W. Dunmore and F. H. Engel, Proc. Inst. of Radio Eng., **11**, p. 467; October, 1923; "Theory of Determination of Ultra-Radio Frequencies by Standing Waves on Wires," A. Hund; B. S. Sci. Paper No. 491, 1924; "Primary Radio-Frequency Standardization by Use of the Cathode-Ray Oscillograph," Grace Hazen and Frieda Kenyon, B. S. Sci. Paper No. 489, 1924.

[2] Horton, Ricker, and Marrison, Bell System Tech. Jour., June, 1923, p. 730, Kendall. U. S. Patent No. 1446752.

60 kc. A sonometer was used as an auxiliary in standardizing piezo oscillators to determine the difference in frequency between the nearest harmonic of the fundamental frequency as given in the harmonic amplifier and the unknown fixed frequency.

1. CIRCUITS AND APPARATUS

The first unit of the harmonic amplifier (fig. 1) used for the low-frequency standardization is made up of four stages. The output from the circuit controlled by the tuning fork or fundamental frequency source is applied to tube 1 through an audio-frequency (iron-cored) transformer. This tube is coupled to tube 2 by an intermediate-frequency transformer (iron-cored). Tubes 2 and 3 are inductively coupled through tuned plate and grid circuits, respectively. Tubes 3 and 4 are resistance coupled through 100,000-ohm resistors.

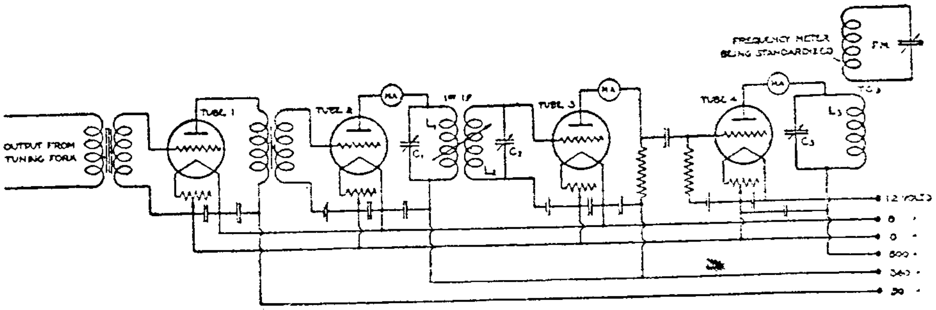

FIG. 1.—*Circuit diagram of harmonic amplifier as used to obtain low frequencies (8–450 kc)*

The tubes used are 5-watt power tubes with the exception of tube 4, which is a 50-watt tube. Where grid batteries are indicated the voltage is chosen of such an amount that the direct plate current is nearly zero with no impressed a. c. voltage; that is, the distortion is produced by the lower curvature of the grid voltage-plate current characteristic.

The values of capacity and inductance of the first tuned stage referred to as the first intermediate frequency (*1st I. F.*, fig. 1) were chosen to cover the range of frequencies 8 to 15 kc, which gives a sufficient number of points for the frequency-meter standardization. Coils having an inductance of approximately 40 millihenries (outside diameter of winding, 6 inches; width of winding, 1 inch) are used for coupling coils L_1 and L_2. Condensers C_1 and C_2 are 0.005 μf variable air condensers with a switch, making possible the addition of a fixed condenser for additional capacity. The tuned circuit in series with the plate of tube 4 is arranged to cover the frequency range 8 to 450 kc. The inductance coils used varied from 0.01 to 24 mh, and have large diameters approximately the size of the coils of the frequency meter to be coupled to them. The capacity was made up of a parallel combination of fixed and variable condensers and was continuously variable up to 0.01 μf. For the range 8 to 450 kc, the frequency meter being standardized is coupled directly to coil L_3, the coupling being adjusted to give a sufficient indication on the indicator.

The second unit, which is a 2-tube resistance-coupled amplifier, is used to extend the range to 4,000 kc. (Fig. 2.) This unit is identical with the last two stages of the low-frequency unit with the exception of the inductances and capacities of the circuits. When this unit is used the coil L_3 is replaced by a coil L'_3 of small diameter similar to coils L_1 and L_2, but having an inductance of approximately 22 mh. This coil has the advantage over the larger size coil of producing a more concentrated field and reduces the interaction with L_1. This unit is coupled to the first unit (fig. 1),

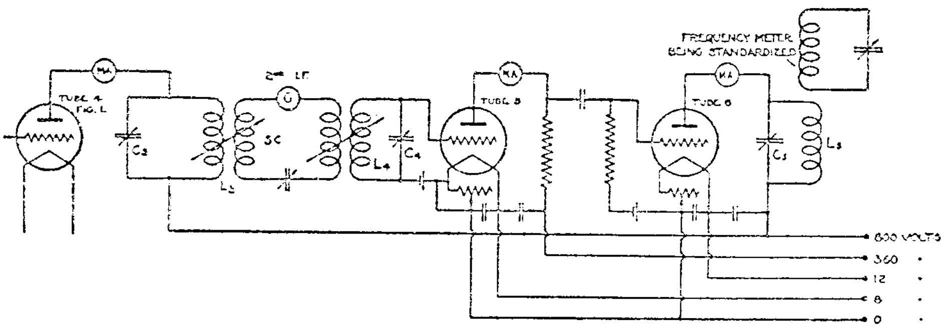

FIG. 2.—*Extension of harmonic amplifier shown in Figure 1 to obtain frequencies to 4,000 kc*

through a tuned selector circuit, *SC*, by means of inductance L_4 which is identical with L'_3. The capacity, C_4, in the grid circuit of tube 5 consists of fixed and variable condensers continuously variable up to 0.0045 μf. This gives a range from approximately 18 to 100 kc for the second intermediate frequency (*2nd I. F.*) values.

The tuned selector circuit [3] through which the two units are coupled consists of a condenser, coil, and resonance indicating device (thermogalvanometer). This circuit serves to suppress other harmonics than the one selected and when calibrated makes it possible to set the circuit (*2nd I. F.*) to any desired harmonic of the first intermediate frequency, thus making the identification of the harmonic in the final stage fairly simple.

A 0.00025 μf condenser, C_5, and coils, L_5, of proper inductance and diameter to be in resonance and give good coupling with the frequency meter under standardization, are used in the plate circuit of the last tube. All battery leads are by-passed with large condensers (about 1 μf).

[3] A Bureau of Standards type L wave meter was used for this purpose.

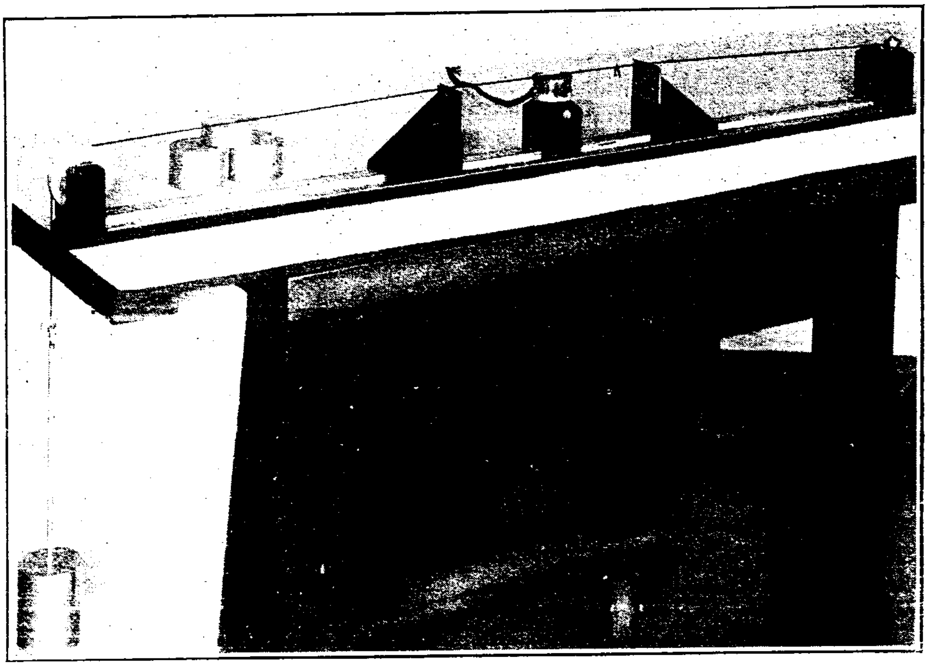

FIG. 3.—*Sonometer used for the determination of the frequency of the beat note produced by two radio frequencies*

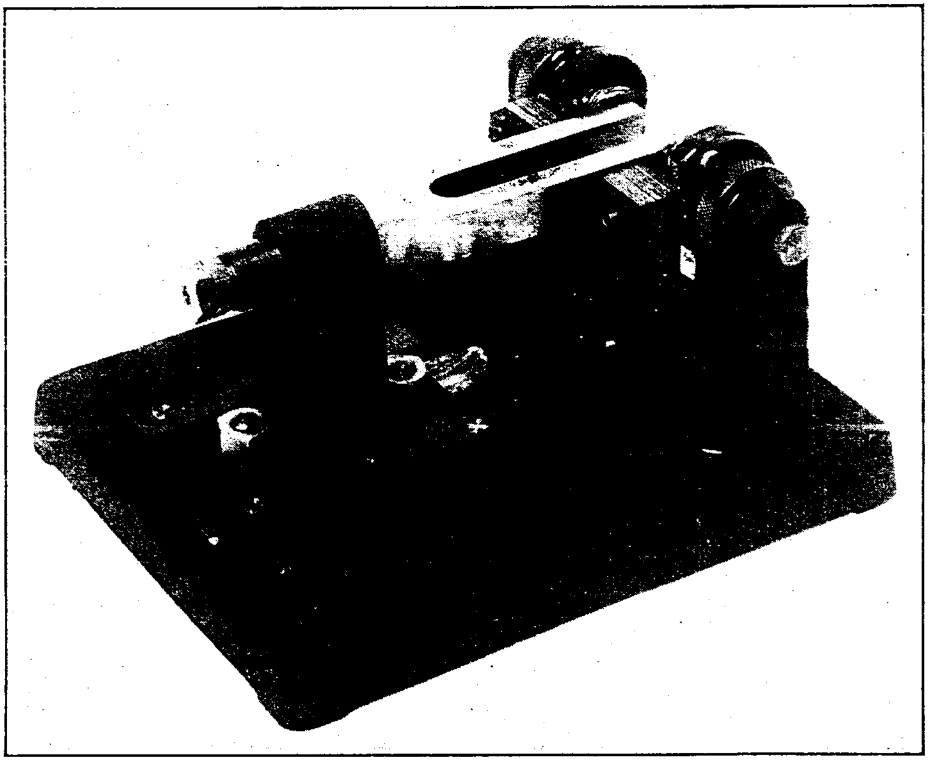

FIG. 4.—*Mounted tuning fork used as the fundamental frequency source*

2. AUXILIARY APPARATUS FOR STANDARDIZATION OF A FIXED-FREQUENCY GENERATOR

An auxiliary device used with the harmonic amplifier to measure a fixed-frequency generator is a sonometer (fig. 3) or monochord having a range from 80 to over 3,000 cycles. It consists of a steel piano wire (approximately 0.026 cm diameter) mounted in a horizontal position and stretched over two brass knife-edges with a known weight giving a definite tension to the wire. The frequency at which the wire vibrates is computed from $f=\frac{1}{2L}\sqrt{\frac{T}{M}}$. L=length between knife-edges; T=tension; M=mass of wire per unit length. To avoid loss in tension due to friction in applying weights, the wire is passed over a ball-bearing pulley. The calibration of the sonometer was checked at several points against a tuning fork of known frequency.

The beat-note frequency to be measured is applied to the sonometer through a telephone receiver magnet mounted at a small distance from the wire. As the length between the knife-edges is varied and the natural period of vibration of the wire approaches the frequency in the telephone, the wire will be set in motion due to the periodic attraction of the steel wire by the telephone magnet.

3. FUNDAMENTAL FREQUENCY SOURCE

The 1,000-cycle [4] standard tuning forks used in this work (fig. 4) were standardized by the sound section of this bureau by comparison with a standard of time. The frequency values for the 100-cycle fork were obtained by comparison with a standard quarter-meter gravity pendulum loaned to the bureau by the Coast and Geodetic Survey.[5]

The electron-tube drive of the 1,000-cycle tuning forks is one in which the reactance between plate and grid is wholly mechanical as in the drive described by Eccles and Jordan.[6] This avoids any possibility of the circuit producing oscillations independent of those actuated by the tuning fork. The 1,004-cycle tuning fork used in this work was calibrated to ±0.12 of a cycle, or 0.01 per cent. It was corrected for temperature changes, using the correction factor of −0.011 per cent per °C. This correction factor is known to a certainty of ±0.004 per cent per °C. The fork was kept at a nearly uniform temperature, so that this correction was small.

This circuit gives sufficient output for satisfactory operation of the harmonic amplifier as shown in Figure 1. For fundamental frequency sources of much less intensity than this further amplification

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[4] Two forks, one of 1,004 and one of 1,025, were used in this work—the drives were identical.

[5] Acknowledgment is made to Dr. C. Moon for the use of this tuning fork and for his determinations of its frequency during its use.

[6] Eccles and Jordan, Electrician, June 20, 1919.

frequency meter standardized, Z, had a range from 12 to 3,100 kc. The frequency meter circuit contained a variable air condenser [9] of 0.0012 μf, with four mica condensers of 0.001, 0.002, 0.004, and 0.008 μf which may be connected in any parallel combination with the variable air condenser, and six interchangeable coils [10] of 0.01 to 128 mh inductance. A sensitive millivoltmeter and crystal detector in series with a pick-up coil coupled to the coil of the frequency meter was used to indicate resonance. The frequency meter is always grounded during use.

Overlaps were obtained by using the 0.001 or 0.002 fixed condensers in parallel with the variable air condenser.

3. RESULTS

The number of frequency values which it is possible to determine using the harmonic amplifier is indicated by the table.

Summary of frequency values obtained in standardization of frequency meter Z by the harmonic amplifier

Coil number	Inductance	Frequency range	Number of observations		Difference in frequency between observations
			1,000 tuning fork	100 tuning fork	
	mh	*kc*			*Per cent*
1	0.01	1,600–3,080	42		2.3
1+0.001 μf		1,170–1,600	31		3.3
2	.05	605–1,170	45		2.2
2+0.001 μf		444– 610	40		2.5
2+0.002 μf		367– 446	31		3.2
3	.36	231– 440	52		1.9
3+0.001 μf		170– 234	37		2.7
3+0.002 μf		141– 171	21		4.7
4	2.44	92– 174	43		2.3
4+0.001 μf		68– 93	37		2.7
4+0.002 μf		56– 68	21		4.8
5	23	31– 56	30	11	2.4
5+0.001 μf		23– 31	13	21	2.9
5+0.002 μf		19– 23	6	18	4.2
6	128.0	12– 23	14	17	3.7
Total		12–3,080	463	67	

Observations averaged every 3° with no fixed condenser, 5° with 0.001 μf, and 7° with 0.002 μf. It should be noted that at the higher-frequency ranges a much larger number of values can be obtained than are needed for the drawing of a calibration curve, since the harmonic from a 1,000-cycle fork, using all of the intermediate frequency points possible, will appear at very small intervals on

[9] B. S. Cir. No. 74, Radio Instruments and Measurements.

[10] B. S. L. C. No. 103, Description of a series of single-layer inductance coils suitable for radio-frequency measurements.

the frequency-meter condenser scale, especially when no fixed condensers are used. The same is true of the 100-cycle fork for the lower frequencies. It should be mentioned that for a frequency meter of the range here standardized it would be more convenient to use a 400-cycle tuning fork as an auxiliary fundamental frequency source instead of the 100-cycle standard, but none was available at this time.

The sources of error in standardization with the harmonic amplifier method are entirely those inherent in the fundamental frequency source and in the reading of the frequency meter under standardization. Since the frequency of the tuning fork may be determined more accurately than the present frequency meter can record, the precision of the frequency measurements can be increased as the design of frequency meters used are improved.

IV. PIEZO OSCILLATOR STANDARDIZATION

The fixed-frequency generators standardized by the harmonic amplifier and sonometer were piezo oscillators. The piezo oscillator [11] is a small, low-power generator with three frequencies determined and controlled by three modes of vibration of the quartz plate. Any one of these frequencies may be chosen by tuning the circuit to very approximately the frequency desired. Since the frequency values from the harmonic amplifier are fixed frequencies determined by the fundamental source it is obvious some variable device is necessary to standardize it against another fixed frequency. The sonometer described in Section II serves this purpose satisfactorily.

1. METHOD

In standardizing a piezo oscillator of unknown frequency an approximate value of its frequency is first determined by direct measurement with a standard-frequency meter. The harmonic amplifier is adjusted to the harmonic most nearly this frequency. A standard frequency meter is coupled to the output of the harmonic amplifier and tuned to resonance with it. The piezo oscillator is placed near the opposite (or grounded) end of the coil of the frequency meter which acts as a filter to other harmonics. The beat note between the harmonic selected and the fundamental of the puzo oscillator is amplified by a 2-tube resistance-coupled amplifier and the output measured by the sonometer in the following manner: The sonometer wire is stretched and its pitch roughly adjusted by ear to that of the beat note by changing the tension and length of the wire, then the telephone-receiver magnet in the output of the amplifier is

[11] Uses and possibilities of piezo-electric oscillators. A. Hund. Proceedings of the Institute of Radio Engineers, 1926. Bureau of Standards Letter Circulars 183, 186, 187.

placed under the wire, and the distance between the knife-edges is varied very slowly until the wire begins to vibrate. For weak signals a small paper rider is used to show the vibration of the wire, while for strong-beat notes a sharper maximum setting is obtained by setting on the maximum sound produced by the vibration of the wire. The length of the wire is measured and the frequency computed. This frequency gives the difference between the harmonic of the fundamental source and the frequency of the piezo oscillator. It is either a plus or minus correction, as is shown by the difference of the frequency of the piezo oscillator determined by the frequency meter reading, from the frequency of the harmonic given by the harmonic amplifier. If the harmonic and frequency meter readings are extremely close it is necessary to choose another harmonic setting to determine the direction of this correction; that is, whether the piezo oscillator frequency is above or below the harmonic frequency.

2. RESULTS

This method of standardizing a fixed-frequency oscillator was found very satisfactory by checking several piezo oscillators. The accuracy of the sonometer need not be high in order to obtain a high degree of precision in the radio range, for example, working with a beat note of 1,000 cycles the sonometer may have an error of 0.5 per cent. At any frequency over 100 kc this would be less than 0.005 per cent error in the radio-frequency determination. Errors in the sonometer may be balanced out by using harmonics above and below the piezo oscillator frequency.

V. COMPARISON OF TWO AUDIO-FREQUENCIES

The harmonic amplifier and sonometer were also used to compare two audio-frequencies, 100 and 1,025 cycles. A beat note was obtained between a harmonic from the output of a 1,025-cycle electron tube driven tuning fork and the fundamental of a radio-frequency generator. This beat note was reduced to zero, this point being indicated by means of a sensitive milliammeter in the plate circuit of a detector tube. The output from the 100-cycle tuning fork was carried through the harmonic amplifier and a harmonic selected near the value of the one selected by the generator. The two frequencies were then combined in a tuned circuit and the beat note produced detected, amplified, and measured by means of the sonometer, as was done with the piezo oscillator. Several combinations of harmonics were used to obtain a mean value with a maximum error of less than 0.02 per cent.

VI. SUMMARY

This paper describes a harmonic amplifier and its application in establishing radio standards of frequency from an audio-frequency source. The results of one frequency meter standardization are summarized briefly. A sonometer, an auxiliary pitch-measuring device, is described, and the method of using the harmonic amplifier with this auxiliary for the standardization of piezo oscillators and comparison of audio-frequencies is given.

The work has shown that radio-frequency meters may be standardized with high precision and ease from a fundamental audio-frequency by the use of a harmonic amplifier. The accuracy of the standardization is limited only by the accuracy of the fundamental frequency source and the precision and accuracy of the frequency meter. The harmonic amplifier is simple and rapid in operation. Fixed-frequency generators, such as piezo oscillators and electron tube driven tuning forks, may also be accurately and rapidly standardized by the use of the harmonic amplifier and the auxiliary sonometer.

WASHINGTON, March 23, 1926.