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Wide-Frequency-Range Tuned Helical Antennas and Circuits*

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TRANSMISSION-LINE circuit elements or, more generally, circuit elements with distributed constants, are used advantageously at very- and ultra-high frequencies. At lower frequencies, except for antennas and occasionally in associated networks, their use is not common for the very good reason that such circuit elements become prohibitively bulky. In antenna applications the large size is tolerated in order to achieve a useable radiation efficiency.

This condition prevails as long as the type of distributed-constant circuit elements under consideration is limited to the conventional coaxial- or parallel-transmission-line type. There is, however, a class of distributed-constant circuit elements, made up of helical conductors with or without cylindrical outer conductors, that can be used with considerable advantage at all radio frequencies up to and including the ultra-high-frequency band. Of particular interest for the present discussion is the case of the helix with a diameter small compared to a wavelength.

Though this class of helical circuit element has seen limited use in applications similar to the ones under discussion at present, it is felt that their potentialities have not been fully appreciated and utilized nor has their theory and fundamental properties been adequately discussed in technical literature.

The helical antenna, with diameter considerably less than a wavelength, radiating predominantly vertical polarization in the normal mode (peak of radiation pattern normal to the helix axis) has several advantages over a conventional dipole when the height must be considerably less than a quarter wavelength. The radiation resistance is about 50-percent greater than a dipole of the same height and the input impedance can be made real so that the problem of matching to a transmission line is simplified. In addition, the helix can be matched by grounding the base of the helix and connecting the transmission line to the proper tap point so that no external matching networks are required.[1]

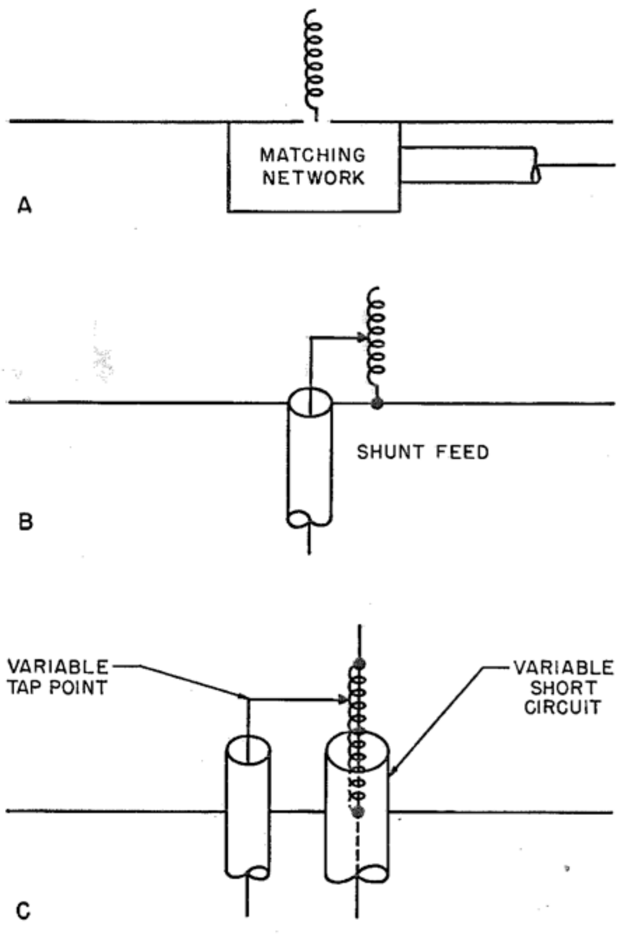

Figure 1—Helical antenna types.

The basic idea of the short resonant helical antenna is not new; for example, Wilson[2] used a helix 2 feet (61 centimeters) high with a 6-foot (183-centimeter) whip to make an efficient 4-megacycle-per-second mobile antenna. It is understood that some radio amateurs use a type similar

* Reprinted from *Convention Record of the IRE 1953 National Convention*, Part 2—Antennas and Communication, pages 42–47. Presented at the National Convention of the Institute of Radio Engineers in New York, New York, on March 23, 1953.

[1] J. F. Morrison and P. H. Smith, "Shunt-Excited Antenna," *Proceedings of the IRE*, volume 25, pages 673–696; June, 1937.

[2] W. R. Wilson, "Solenoid-Whip Aerial," *Electronics*, volume 14, pages 56–64; January, 1941.

to Wilson's or a complete helix on the 4-megacycle and 14-megacycle bands. However, the small-diameter helix does not seem to have been discussed extensively in the literature, in contrast with the work of Kraus[3] and others on the large-diameter helix.

The two general types are shown in Figure 1. Type A generally requires an external matching network and for some applications is less desirable than type B. Type B uses shunt feed so that the matching network is part of the radiating structure. In addition, type B can be made tunable over wide frequency ranges as shown in Figure 1C by using a variable tap point and a variable short circuit. The lower frequency limit is obtained when the length of wire in the helix is approximately a quarter wavelength, while the upper limit is obtained when the height is a quarter wavelength. With proper design, tuning ranges up to 100 to 1 can be obtained.

1. Velocity of Propagation

The phase velocity along the axis of the helical antenna can be obtained from the previous work on coaxial lines with helical inner conductors and also from the work on the helix for use in traveling-wave tubes.[4–6] The velocity is given by

$$(c/V)^2 = 1 + (M\lambda/\pi D)^2. \tag{1}$$

M is a function of the helix diameter, frequency, and number of turns per unit length, and is given in Figure 2. Also shown is the ratio (approximate) of the apparent velocity along the wire to the velocity of light, V_w/c. This ratio is close to 1 for the helices used in traveling-wave tubes ($M \gg 1$), less than about 1.3 for the usual coaxial line with helical inner conductor, but may be greater than 2 for some helical antennas. The exact expression for V_w/c is

$$V_w/c = \left[\frac{1+(N\pi D)^2}{1+(M\lambda/\pi D)^2}\right]^{1/2}. \tag{2}$$

[3] J. D. Kraus, "Antennas," McGraw-Hill Book Company, Incorporated, New York, New York, First Edition; 1950.

[4] J. R. Pierce, "Traveling-Wave Tubes," D. Van Nostrand Company, Incorporated, New York, New York, First Edition; 1950: page 229.

[5] J. R. Pierce, "Theory of the Beam-Type Traveling-Wave Tube," *Proceedings of the IRE*, volume 35, pages 111–123; February, 1947.

[6] L. L. Chu and J. D. Jackson, "Field Theory of Traveling-Wave Tubes," *Proceedings of the IRE*, volume 36 pages 853–863; July, 1948.

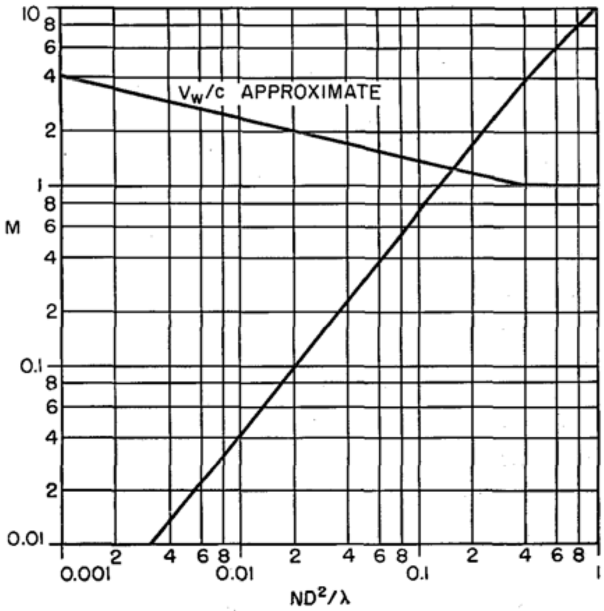

Figure 2—Relative velocity along the wire (V_w/c) and quantity M used in calculating the velocity along the axis.

The approximation in Figure 2 is obtained by neglecting (1) in comparison with the other factors.

When the helix is used with a ground plane, the height must be a quarter wavelength at the velocity given by (1) to obtain a real input

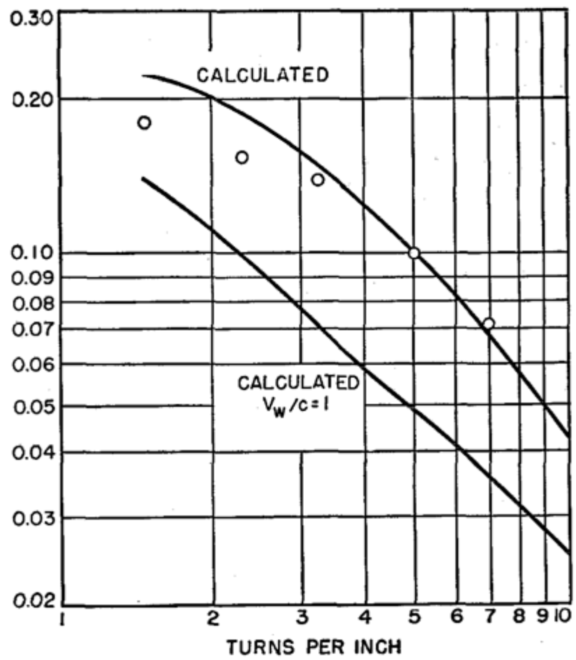

Figure 3—Helical antenna above a ground plane—height in wavelengths at resonance versus turns per inch.

impedance

$$\frac{h}{\lambda}=\frac{1}{4c/V}=\frac{1}{4[1+20(ND)^{2.5}(D/\lambda)^{1/2}]^{1/2}}. \quad (3)$$

The last expression holds when $ND^2/\lambda \leqslant 1/5$. Figure 3 shows measured and calculated values of height versus number of turns per inch. The curve near the measured points was calculated using (3), while the lower curve was calculated assuming that $V_w/c = 1$. As can be seen from the figure, the measured height is sometimes twice the height predicted using $V_w/c = 1$.

Figure 4 shows how the calculated resonant frequency varies with the number of turns per inch while holding the wire length constant. If V_w/c were a constant, each curve would be a straight line with zero slope.

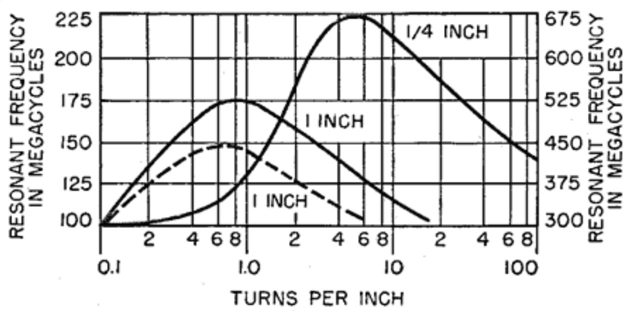

Figure 4—Resonant frequency versus turns per inch with constant wire length. Helix diameter is shown on the curves. The resonant-frequency scale for the dashed curve is at the right; for the other curves use the left scale.

2. *Radiation Resistance and Effective Height*

The effective height[7] of a short dipole above a perfect ground is $l_{\text{eff}} = h/2$. The effective height of a resonant helical antenna is $l_{\text{eff}} = 2h/\pi$ because the current distribution is sinusoidal instead of linear. The radiation resistances are given by

$$\left.\begin{aligned} R_r &= (20h/\lambda)^2 \text{ for short dipole,} \\ R_r &= (25.3h/\lambda)^2 \text{ for resonant helix.} \end{aligned}\right\} (4)$$

For heights near a quarter wavelength, the numerical factor in the resonant helix equation should be changed to 24 in order to get 36 ohms when the height is a quarter wavelength.

[7] See, for example, S. A. Schelkunoff and H. T. Friis, "Antennas, Theory and Practice," John Wiley and Sons, Incorporated, New York, New York, First Edition; 1952: page 309.

3. *Polarization*

For a helix in free space, the ratio of the vertically polarized field to the horizontally polarized field is given by

$$\frac{E_v}{E_h}=\frac{J_0(\pi D/\lambda)}{(N\pi D)J_1(\pi D/\lambda)}\approx\frac{\lambda}{5ND^2}. \quad (5)$$

The approximate result, good for small diameters, has been given by Wheeler.[8] If the helix is resonant, circular polarization is obtained when the over-all height is about 0.9 times the diameter.

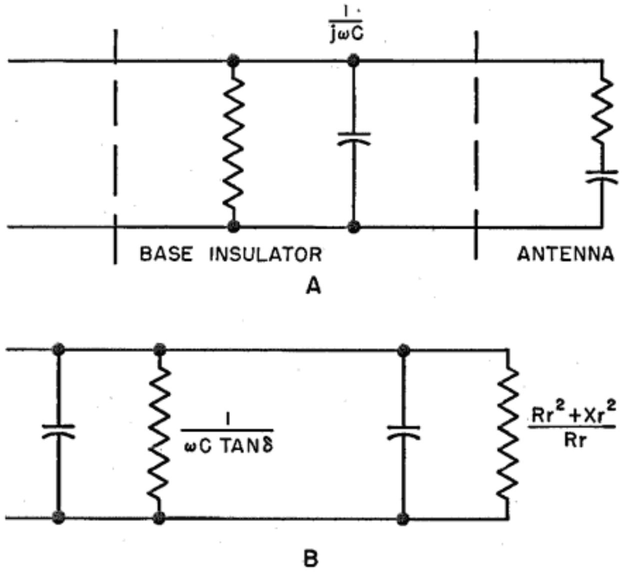

Figure 5—Circuits of a short dipole and base insulator. *A*—actual circuit. *B*—equivalent circuit.

When the helix is used with a ground plane, the horizontal polarization is weakened considerably if the height of the helix is small. For this case the pattern of the horizontally polarized field is

$$E_h' \approx E_h\ (2\pi h/\lambda) \sin\theta \cos\theta. \quad (6)$$

The maximum value of this pattern occurs at $\theta = 45$ degrees. The pattern of the vertically polarized field is

$$E_v' \approx E_v\ \pi \cos\theta. \quad (7)$$

The ratio of the horizontally polarized field at $\theta = 45$ degrees to the vertically polarized field at $\theta = 0$ degrees is

$$\left(\frac{E_h'}{E_v'}\right)_{\max}\approx\frac{5ND^2h}{\lambda^2}. \quad (8)$$

[8] H. A. Wheeler, "Helical Antenna for Circular Polarization," *Proceedings of the IRE*, volume 35, pages 1484–1488; December, 1947.

Thus, if circular polarization were obtained with a helix 0.1 wavelength high in free space, the horizontally polarized field at $\theta = 45$ degrees would be 20 decibels below the vertically polarized field at $\theta = 0$ degrees, when the helix is used with a ground plane.

4. *Losses*

4.1 Base-Insulator Losses

Low efficiency may be obtained with short dipoles because of power loss in the insulator used to support the dipole. The choice of dielectrics is limited because of mechanical requirements and a power factor less than 10^{-3} is probably unobtainable at present. The equivalent circuit is shown in Figure 5. For this circuit,

$$P_l/P_r = (\omega_c \tan \delta)\ (R_r^2 + X_r^2)/R_r. \tag{9}$$

For a 35-foot (10.6-meter) whip 2 inches (5 centimeters) in diameter, below about 3 megacycles, with a 40-micromicrofarad base insulator of power factor 10^{-3}, and using the following,

$$\left.\begin{aligned} R_r &= (20\ h/\lambda)^2, \\ X_r &= -\ Z_0 \cot\ (2\pi h/\lambda), \\ Z_0 &= 60\ [\ln\ (4h/d) - 1], \end{aligned}\right\} \tag{10}$$

this becomes

$$P_l/P_r \approx 1.25/F_{mc}^3. \tag{11}$$

At 1 megacycle the efficiency is about 50 percent, while at 300 kilocycles the efficiency is about 2 percent (17 decibels loss).

In addition to the base-insulator loss, there will be further losses in the network used to match the antenna to a transmission line. In contrast, a helix 35 feet (10.6 meters) high made of 0.5-inch (12.7-millimeter) wire wound on a form one foot (30 centimeters) in diameter with 1.6 turns per inch (0.63 turns per centimeter) has a calculated total efficiency of about 5 percent (13 decibels loss) at 300 kilocycles.

4.2 Helix Losses

The ohmic losses in the metal of a short dipole are ordinarily quite small, but the losses in the helical antenna may be appreciable because the wire diameter is usually much smaller than the diameter of a dipole of the same height. The loss can be calculated[9] assuming that the current distribution is sinusoidal and neglecting proximity effects.

$$\frac{P_l}{P_r} = \frac{2\,10^{-4}(V_w/c)}{dF_{mc}^{1/2}(h/\lambda)^2}. \tag{12}$$

This equation gives the ratio of power dissipated in the copper to the power radiated. The efficiency of the helix is therefore $1/(1 + P_l/P_r)$. Figure 6 is a plot of height versus resonant frequency for 50-percent efficiency assuming that $V_w/c = 1$.

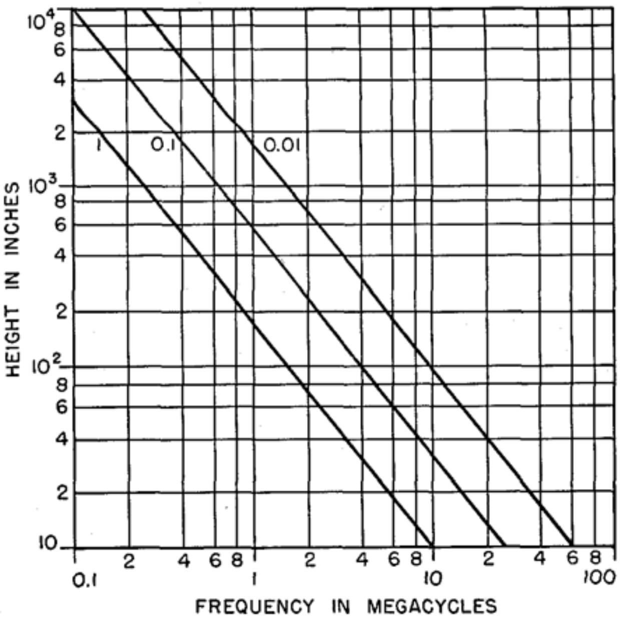

Figure 6—Height versus resonant frequency for 50-percent efficiency, assuming $V_w/c = 1$. Wire diameter is shown on the curves.

Measurements were made at 100 megacycles of the power radiated by helices of various heights and wire diameters compared to the power radiated by a matched quarter-wavelength dipole. The base of each helix was soldered to the ground plane and the inner conductor of the 50-ohm transmission line connected to the proper tap point on the helix to get a standing-wave ratio less than 1.5. The results are shown in Figure 7. The solid curves are calculated using (12) ~~(9)~~ above. In most cases, the agreement is fair except for the thinnest wire, where the measured points are consistently low.

5. *Q and Tap Point*

The Q of an antenna is of interest because it limits the bandwidth that may be used. The Q

[9] See, for example, footnote reference 7, page 338.

of the helical antenna[10] can be calculated if some assumptions and approximations are made.

The antenna is assumed to be equivalent to a resonant line a quarter-wavelength long. The input resistance ($\lambda/4$ away from the open circuit) is[11]

$$R_{\text{base}}/Z_0 = \pi/4Q. \tag{13}$$

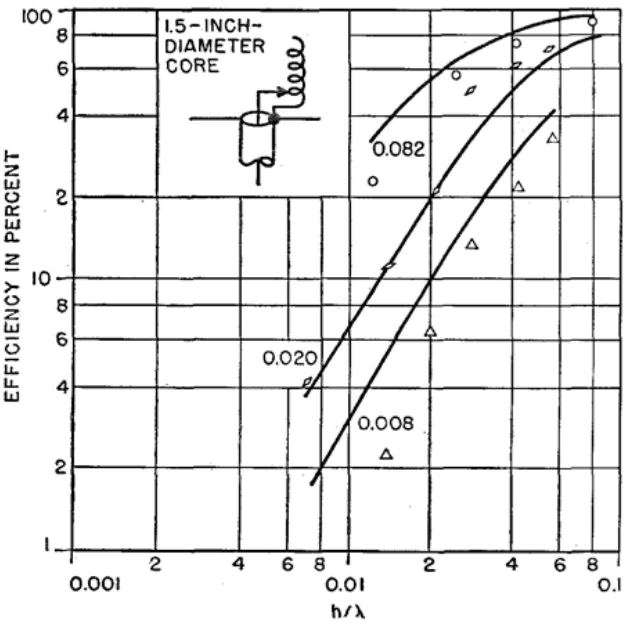

Figure 7—Measured efficiency versus height. Wire diameter is shown on the curves.

R_{base} is the sum of radiation resistance and wire resistance, referred to the base of the antenna. For a resonant antenna, $R_w = R_0\, l/2 = R_0\, (\lambda/8) \times (V_w/c)$.

$$R_{\text{tap}} = \frac{Z_0^2 \sin^2 \theta_1}{R_{\text{base}}} = \frac{4}{\pi} Q Z_0 \sin^2 \theta_1. \tag{14}$$

The characteristic impedance that best fits the experimental data is the helical-transmission-line characteristic impedance derived previously.[12] This characteristic impedance is also given by

$$Z_0 = 60\,[\ln(4h/D) - 1]\,(c/V). \tag{15}$$

[10] In this paper, Q means unloaded Q. When driven by a generator with zero internal resistance, the radiated power is 3 decibels below the maximum radiated power at two frequencies F_0/Q apart. When driven by a generator with internal resistance equal to the antenna resonant resistance, the radiated power is 3 decibels below the maximum radiated power at two frequencies $2F_0/Q$ apart.

[11] "Reference Data for Radio Engineers," Federal Telephone and Radio Company, New York, New York, Third Edition; 1949: page 312.

[12] W. Sichak, "Coaxial Line with Helical Inner Conductor," to be published in *Proceedings of the IRE.*

The first factor in this equation is the familiar expression that predicts the reactance of ordinary dipoles. The (c/V) factor takes account of the fact that the axial velocity of the helical antenna is less than that of the ordinary dipole.

Figure 8 shows how the Q varies with h/λ for one of the antennas used in obtaining the data for Figure 7. The agreement is fair using (13). When (14) is used to predict the tap point θ_1, fair agreement is also obtained except when the diameter is large and/or c/V is large.

6. *Circuit Applications*

Important applications of helical transmission lines are delay lines, wide-tuning-range resonant circuits, and the extension of transmission-line techniques to frequencies as low as 300 kilocycles.

A delay line $1\frac{5}{8}$ inches (4.13 centimeters) in diameter for use at 10 megacycles was built with the following characteristics: characteristic impedance, 5000 ohms; a delay of 0.2 microsecond per foot (0.66 microsecond per meter), and an attenuation of 0.9 decibel per microsecond.

Figure 9 shows the resonant frequency versus linear movement of a short-circuiting plunger for five quarter-wavelength resonators. The helical inner conductors were made with different configurations—some were wound with constant pitch, some with a constantly varying pitch, and others with sections of different pitch. One of the

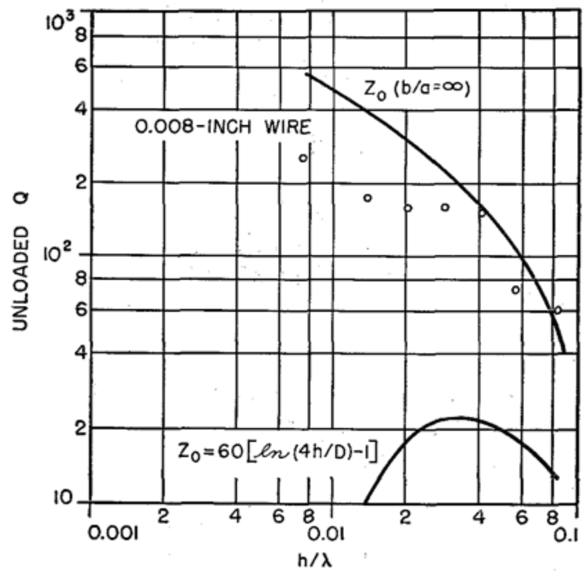

Figure 8—Measured Q versus height.

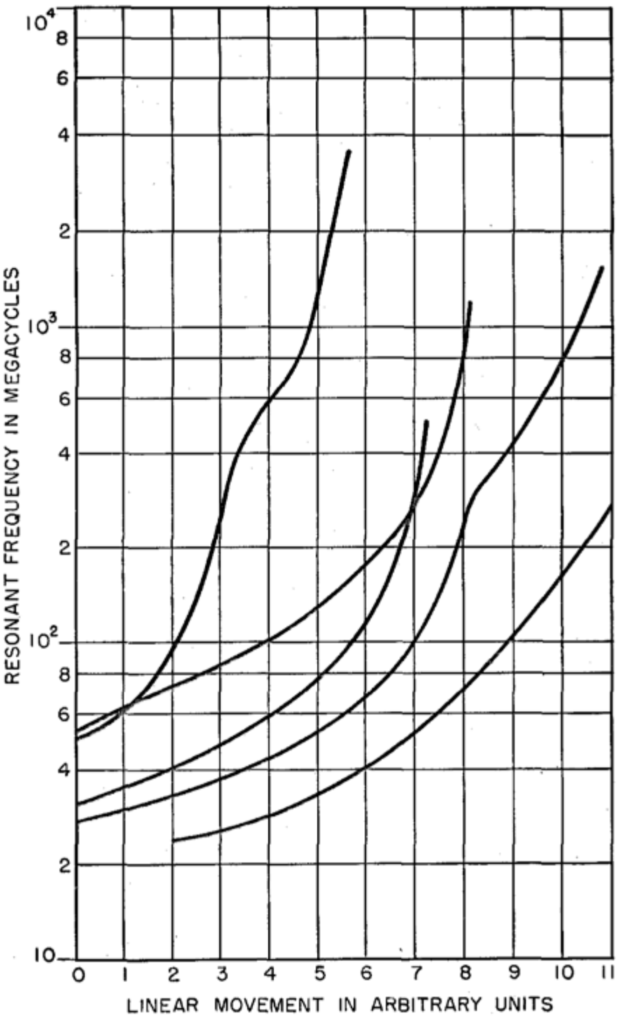

Figure 9—Resonant frequency versus plunger movement for five quarter-wavelength resonators.

resonators shown tuned from 50 megacycles to 3500 megacycles—a range of 70/1.

The tuning range is, approximately:

$$\frac{f_{\max}}{f_{\min}} = \frac{\lambda_{\max}}{\lambda_{\min}} \approx \frac{l}{h} \approx c/V. \tag{16}$$

Thus with proper design, tuning ranges of 100/1 are possible.

7. *Acknowledgment*

Acknowledgment is due to R. A. Felsenheld, L. Juhas, and W. Huey for making the measurements reported in this paper.

8. *Glossary*

c = velocity of light
d = wire diameter in inches
D = mean helix diameter in inches
F_{mc} = frequency in megacycles
h = height
l_{eff} = effective height
n = number of turns per inch
P_l/P_r = ratio of power dissipated to power radiated
R_r = radiation resistance
R_0 = resistance per unit length
V = phase velocity along the axis
V_w = apparent phase velocity along the wire
ω = $2\pi \times$ frequency
X = reactance
Z_0 = characteristic impedance
$\tan\delta$ = power factor
λ = wavelength
θ_1 = angular distance from short-circuited end to tap point.

Corrections:

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THE second-from-last sentence in section 4.2 on page 297 should be, "The solid curves are calculated using (12) above." The reference to (9) is incorrect.

Fig 4. on p296 was originally inserted in section 2. It has been moved to the end of section 1.