A LOW-FREQUENCY HELICAL ANTENNA FOR SUB-SURFACE COMMUNICATION

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The purpose of this paper is to develop a simple antenna structure of limited dimension suitable for low frequency and under-ground communication. The closed-wound helical antenna of length small compared to wavelength is found to be a better radiator compared to a linear antenna of same length. Field expressions for both dissipative and non-dissipative media are calculated and tabulated. A chart is provided to study the reflection effect and a curve is plotted showing the relative strength of helical antenna with respect to the linear antenna. The assumption of uniform earth's characteristic is made through out the analysis.

In the recent years radio communication within the earth's crust is getting importance mainly to protect communication system from hazards either natural (cyclones, etc.) or man-made (nuclear explosion). The high conductivity of earth's soil attenuates the "radiated" signal strength in an exponential manner, along with a large dissipation in the 'induction field' and 'static field'. The attenuation increases with frequency $\left(\alpha = \sqrt{\frac{\omega\mu\sigma}{2}}\right.$ for $\left.\sigma >> \omega\epsilon\right)$ hence to minimise attenuation, transmitting frequency has to be kept as low as possible. But low frequency antenna, to be highly efficient, is very big in dimension. For Sub-surface Communication such mamoth structure is difficult to place underground-enormous labour will be required along with the difficulties like insulating the entire structure covering a very large area, supporting the structure, etc. So we have two conflicting situations—minimising attenuation at the cost of efficiency of the antenna.

It is the aim of this paper to develop a moderate efficiency antenna at low frequency within a limited space and a practicable size. In section II, such an antenna is described and 'near-zone' and 'far zone' field expressions are obtained. In latter sections, the effect of ground, frequency and other parameters have been discussed.

ANTENNA DEVELOPMENT AND FIELD FORMULAS

It has been suggested[1] that simple insulated wire parallel to the interface will be an efficient transmitting antenna. In view of the terrific attenuation associated with communication at higher frequencies, transmitting frequency has to be kept below 1 Mc/s. The ground conductivity is varying from place to place but we may fix the working frequency on the basis of a moderate conductivity. It should be kept in mind that for communication purpose, the frequency should be much above the highest frequency of the message to be communicated. Hence for voice transmission, it is safe to use frequency above 50 Kc/s. In practice the frequency is kept between 100 Kc/s and 300 Kc/s and in particular cases, even slightly higher. At this frequency range, the linear antenna of moderate length will show poor efficiency which can be increased by increasing the effective length still keeping the physical length small by winding wire of suitable diameter on a non-conducting cylindrical structure. Such an antenna is one extreme form of helical antenna in which the successive turns are so close together that it can be thought as a number of loops on the same axis, one above the other. The increase in effective length over the physical length is resulted from the contributions of the loops, hence will depend on the parameters of the loop (*i.e.* helix). For wavelength very large compared to dimension, the effect of one single loop can be neglected but a large array is expected to increase the effective radiation.

The important works [2,3] on helical antenna show that the fundamental advantage of such type of antenna is to reduce the interference by echoes—the antenna has been used primarily for high frequency of the orders of several megacycles. At lower frequencies (Physical length $L << \lambda$), the helical antenna with close spacing of the successive turns can be thought[4] as an array of the combination of a loop and a linear antenna as shown in Fig. 1(b). Hence the resultant field expression due to complete helical structure can be obtained by multiplying the resultant field due to the linear current element of length '*d*' and the loop of diameter D. Since the turns are placed side by side the spacing '*d*' is nothing but the diameter '*d*' of this wire.

The distant electric field due to current element of moment Id ($d << \lambda$) can be written as[5]

$$E_\theta = j\,\frac{\omega\mu Id}{4\pi}\left(\frac{1}{r}+\frac{1}{\gamma r^2}+\frac{1}{\gamma^2 r^3}\right)e^{-\gamma r}\sin\theta \qquad (1)$$

when γ is the propagation constant of the medium. Due to the current element there will be no E_ϕ component, when $E_\theta = 0$, every where for a current carrying loop. Since $\lambda >> D$, ($S=\frac{1}{4}\pi D^2$), it may be assumed that uniform current is flowing and the distant electric field can be written as[5]

$$E_\phi = -j\,\frac{\omega\mu\gamma Is}{4\pi}\left(\frac{1}{r}+\frac{1}{\gamma r^2}\right)e^{-\gamma r}\sin\theta \qquad (2)$$

(1) and (2) can be splitted up into two componests, one induction field and the other radiation field.

$$E\theta_I = j\,\frac{\omega\mu Id}{4\pi\,\gamma r^2}\,e^{-\gamma r}\sin\theta \qquad (1a)$$

$$E\theta_R = j\,\frac{\omega\mu Id}{4\pi r}\,e^{-\gamma r}\sin\theta \qquad (1b)$$

$$E\phi_I = -j\,\frac{\omega\mu Is}{4\pi r^2}\,e^{-\gamma r}\sin\theta \qquad (2a)$$

$$E\phi_R = -j\,\frac{\omega\mu\gamma Is}{4\pi r}\,e^{-\gamma r}\sin\theta \qquad (2b)$$

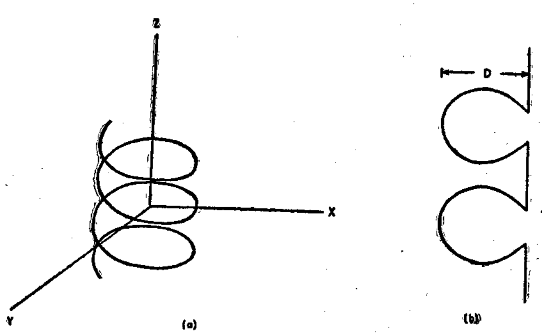

FIG. 1 (*a*, *b*)—Helix and its approximation at low frequency and close spacing.

The expressions can be rewritten by substituting $\alpha + j\beta$ for γ, where α is the attenuation constant and $\beta \left(= \frac{2\pi}{\lambda} \right)$ phase constant. Since interest lies only in field strengths, the real parts are considered. Hence above expressions are written as

$$\left| E\theta_{I} \right| = \frac{\omega\mu Id}{4\pi\,(\alpha^2+\beta^2)^{\frac{1}{2}}} \; \frac{e^{-\alpha r}}{r^2} \; \sin\theta \tag{3a}$$

$$\left| E\theta_{R} \right| = \frac{\omega\mu Id}{4\pi} \; \frac{e^{-\alpha r}}{r} \; \sin\theta \tag{3b}$$

$$\left| E\phi_{I} \right| = \frac{\omega\mu Is}{4\pi} \; \frac{e^{-\alpha r}}{r^2} \sin\theta \tag{4a}$$

$$\left| E\phi_{R} \right| = \frac{\omega\mu\;(\alpha^2+\beta^2)^{\frac{1}{2}}\; Is}{4\pi} \; \frac{e^{-\alpha r}}{r} \sin\theta \tag{4b}$$

The resultant field strnegth (induction or radiation) can be obtained by taking the vector sums of the contributions of the liear element and loop. If E_I and E_R respresent respectively the resultant induction field and radiation field for a single combination of a linear element and loop, the expressions are

$$E_I = \frac{\omega\mu\, d\; e^{-\alpha r}}{4\,\pi r^2\,(\alpha^2+\beta^2)^{\frac{1}{2}}} \left(1 + \frac{S^2\,(\alpha^2+\beta^2)}{d^2} \right)^{\frac{1}{2}} I \sin\theta \tag{5a}$$

$$E_R = \frac{\omega\mu\, d\; e^{-\alpha r}}{4\,\pi\, r} \left(1 + \frac{S^2\,(\alpha^2+\beta^2)}{d^2} \right)^{\frac{1}{2}} I \sin\theta \tag{5b}$$

The expressions for non-dissipative medium, can be find out by putting $\alpha = 0$ and $\beta = \frac{2\pi}{\lambda}$. To simplify the expressions for dissipative medium the displacement current is assumed to be negligible compared to conduction current. With this assumption $\alpha = \beta = \left(\frac{\omega\,\mu\,\sigma}{2} \right)^{\frac{1}{2}}$ for $\frac{\sigma^2}{\omega^2\,\epsilon^2} >> 1$. The substitution of α and β in (5a) and (5b) makes the expressions for dissipative medium as

$$E_I = \frac{\omega\,\mu\, d}{4\,\pi\,(\omega\mu\sigma)^{\frac{1}{2}}} \left(1 + \frac{S^2\,\omega\mu\sigma}{2\,d^2} \right) \frac{e^{-\left(\frac{\omega\mu\sigma}{2}\right)^{\frac{1}{2}} r}}{r^2} \;\mathrm{I}\,\sin\theta \tag{6a}$$

and

$$E_R = \frac{\omega\mu\, d}{4\,\pi} \left(1 + \frac{S^2\,\omega\mu\sigma}{2\,d^2} \right) \frac{e^{-\left(\frac{\omega\mu\sigma}{2}\right)^{\frac{1}{2}} r}}{r} \;\mathrm{I}\sin\theta \tag{6b}$$

after expanding binomially and neglecting higher terms, containing $\frac{S^2\ \omega\mu\sigma}{2\ d^2}$ $= \frac{\pi^2\ D^4\ \omega\mu\sigma}{32\ d^2} << 1$ for the values of the parameters related with sub-surface communication (for $\lambda >> D >> d$). The expressions for non-dissipative medium can also be simplified in a similar fashion.

The field due to entire helical structure can be had on multiplying (6*a*) and (6*b*) by the array factor. The array factor can be obtained by replacing the combination of linear element and loop by isotopic radiators (Fig. 2), when the phase difference between successive sources are given by $(\psi - \xi)$

when $\psi = \beta d \cos\theta$ = Phase by which contribution from A_2 leads A_1

and ξ = progressive phase delay between consequetive sources along the helix $= \beta\,\pi\,D$.

For n number of turns, the array factor

$$|S| = \frac{\sin \frac{n}{2} (\psi - \xi)}{\sin \frac{1}{2} (\psi - \xi)} = \sin \frac{n\pi^2 D}{\lambda} \Big/ \sin \frac{\pi^2 D}{\lambda} \text{ since } d\cos\theta << \pi D$$

$= n$, since $n\ D << \lambda$, and all individual elements are excited in the same phase.

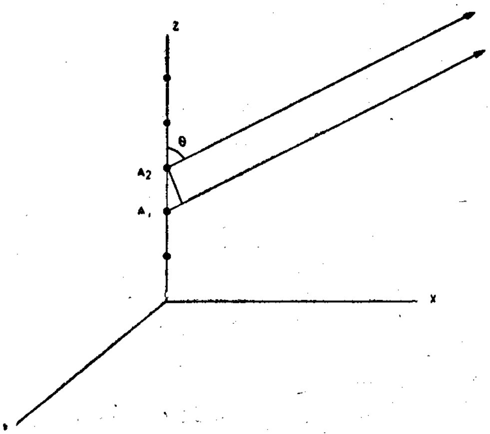

FIG. 2—A linear array of equispaced isotropic radiators.

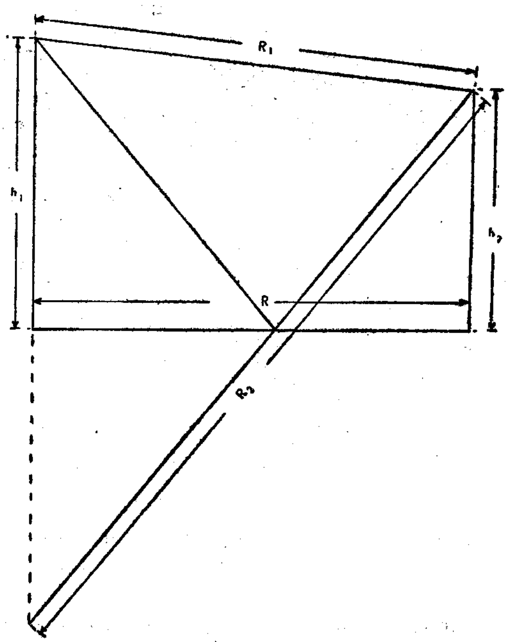

FIG. 3—Illustrating the image theory of reflection.

TABLE 1

ELECTRIC FIELD STRENGTHS OF DIFFERENT ANTENNAS

Type of Antenna	Non-Dissipative medium		Dissipative medium	
Electric field component	Induction Field V/M	Radiation field V/M	Induction field V/M	Radiation field V/M
Loop (Dia : D) E_ϕ	$\frac{\pi f\mu D^2}{8}\frac{\sin\theta}{r^2} I$	$\frac{\pi^2 f\mu D^2}{4\lambda}\frac{\sin\theta}{r} I$	$\frac{\pi f\mu D^2}{8}\frac{e^{-\sqrt{\pi f\mu\sigma}r}}{r^2} I \sin\theta$	$\frac{\pi^{3/2} f^{3/2}\mu^{3/2}\sigma^{1/2} D^2}{4\sqrt{2}}\cdot\frac{e^{-\sqrt{\pi f\mu\sigma}r}}{r} \times I\sin\theta$
Linear Antenna (Length : L) E_θ	$\frac{Lf\lambda\mu}{4\pi}\frac{I\sin\theta}{r^2}$	$\frac{Lf\mu}{2}\frac{I\sin\theta}{r}$	$\frac{L}{2\sqrt{2}}\sqrt{\frac{f\mu}{\pi\sigma}}\cdot\frac{e^{-\sqrt{\pi f\mu\sigma}r}}{r^2}\cdot \times I\sin\theta$	$\frac{Lf\mu}{2}\frac{e^{-\sqrt{\pi f\mu\sigma}r}}{r}\cdot I\sin\theta$
Helix (Dia : D Length : L)	$\frac{Lf\lambda\mu}{4\pi}\left(1+\frac{1}{8}\frac{\pi^4 D^4}{\lambda^2 d^2}\right)\times\frac{I\sin\theta}{r^2}$	$\frac{Lf\mu}{2}\left(1+\frac{1}{8}\frac{\pi^4 D^4}{\lambda^2 d^2}\right)\frac{I\sin\theta}{r}$	$\frac{L}{2\sqrt{2}}\sqrt{\frac{f\mu}{\pi\sigma}}\cdot\frac{e^{-\sqrt{\pi f\mu\sigma}r}}{r^2}\left(1+\frac{\pi^2 D^4\omega\mu\sigma}{32\, d^2}\right) I\sin\theta$	$\frac{Lf\mu}{2}\, e^{\sqrt{\pi f\mu\sigma}r}\frac{1}{r}\left(1+\frac{\pi^2 D^4\omega\mu\sigma}{32\, d^2}\right) I\sin\theta$

Therefore the field expression for the complete helix can be obtained by multiplying the above expressions by n. A comparative idea of the field strengths due to helix and linear antenna (same length and loop of that diameter) can be obtained from Table 1 for both dissipative and non-dissipative media.

In this case, the beam is elliptically polarised since E_θ and E_ϕ are in phase quadrature. It will be found later that by adjusting the variable parameters we can equalise the contributions from the two components, and under this condition the polarisation will be circular. To make the receiving antenna efficient, it is also made the same type as the transmitting antenna. But there is not much difficulty if we cannot achieve high efficiency, provided the S/N ratio of the receiver is high enough. The effective capture area of a receiving antenna can be increased to a much larger value if use is made of a high permeability core for the helix.

EFFECT OF REFLECTION AT THE EARTH AIR INTERFACE

Since in sub-surface communication the antenna has to be placed near the interface (compared to wavelength, the effect of ground reflection has to be considered. To simplify the calculation, the reflected wave may be considered to be generated by an image antenna located above the surface of the ground. In Fig 3, when the antenna is in the dissipative medium, its image will be in non-dissipative medium and vice versa. It can be shown[6] that if obervations are to be made at large distances so that $R_1 \approx R_2 = R$, the difference between R_1 and R_2 only affects the phase difference between two signals—one direct and the other reflected at the interface—and the phase difference can be expressed as $\frac{4\pi h_1 h_2}{\lambda R}$ (assuming $h_1 + h_2 << R$). If Γ be the reflection coefficient, the ratio of the resultant field to direct field can be written[6] as

$$\left(1 + \Gamma e^{-j\frac{4\pi h_1 h_2}{\lambda R}}\right)$$

Γ has both magnitude and phase. Hence writing $\Gamma = q\, e^{-j\phi}$ the magnitude of the ratio is ,

$$\left[1 + q^2 + 2q \cos\left(\phi + \frac{4\pi h_1 h_2}{\lambda d}\right)\right]^{\frac{1}{2}}$$

Here in this case wavelength is so large compared to h_1 or h_2 and provided the distance of observation is large (compared to antenna length), the contribution by the term $\frac{4\pi h_1 h_2}{\lambda d}$ can be neglected. Curves are plotted (Fig. 4) for different values of phase angle to show the relative variation of magnitude of the resultant field strength with different reflection coefficients. Of course the plot is made for a typical set of values for h_1, h_2, R and λ. The frequency is kept at 200 Kc/s, and $h_1 = h_2$ =10 meters. Distance of observation was 100 meters. In practice the distance R is larger, so that the approximations hold good over a large range of transmitting frequency, and the curves can be used with a fair accuracy for the frequency range in which we are interested.

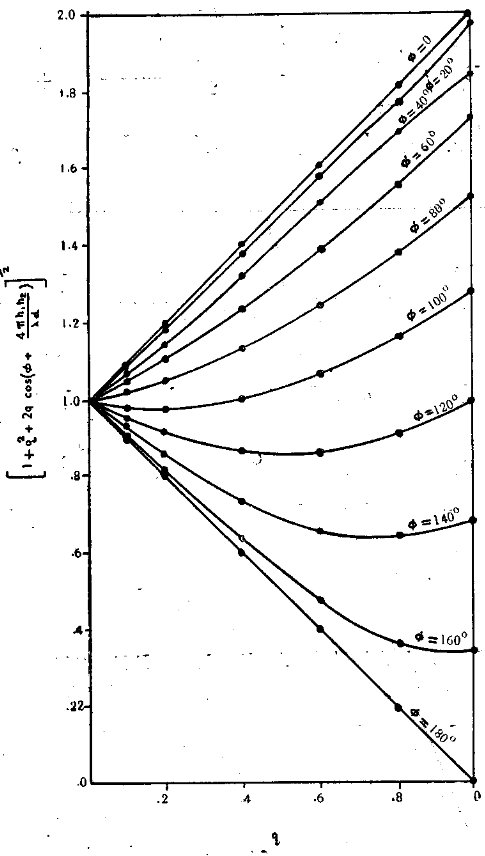

FIG. 4—Chart showing the effect of magnitude and phase of the reflection coefficients on the magnitude of resultant field strength.

Ground reflection coefficient depends[5] on angle of incidence apart from depending on ground conductivity and relative dielectric constant. Though the expression can be thought to be free from frequency variation (in the desired frequency range), yet q itself is a frequency dependent parameter. But the curves will be useful still, since the value of q may shift without altering the character of the curves. q values will be different in different cases depending on the medium in which the source is placed and the reflection coefficient at the interface. In order to use the curves it is only required to know the magnitude and phase value of q in that particular case.

DISCUSSIONS

From Table 1, it can be seen that either the induction field or radiation field of a helical antenna depends not only on the frequency (wave-length), but also on the diameter of the helix and even on the diameter of the wire used to wind the helix. The Table 2 and Table 3 show the effects of various parameters (such as frequency, diameter of helix, diameter of the wire, length of the antenna) on the field expressions for dissipative and non-dissipative medium respectively. From these tables, it is at once apparent that in non-dissipative case, the response of helical antenna of reasonable diameter is approximately equal to that of a linear antenna of same physical length at lower end of the frequency range, *i.e.* at 100 Kc/s. An experiment was conducted to verify the above conclusions qualitatively. An 80 cms. long cylindrical wooden structure was wound with a wire of diameter 0·102 cms. when the diameter of the helix was 10 cms. The observations were taken only in the induction field some more than 10 meters away from the source and it has been found that at 200 Kc/s, the linear antenna and the helix antenna give more or less the same field strength as detected by a calibrated receiver for C.W. operation. Further, using different frequencies at 200 Kc/s, 300 Kc/s and 400 Kc/s with the same helical antenna, it was observed that the helical antenna gives a higher field strength compared to linear antenna of same physical length as the transmitter frequency increases. The observed results were in good agreement with the theoretical calculations as given in Table 3.

TABLE 2

FIELD EXPRESSION FOR HELIX AND LINEAR ANTENNA OF DIFFERENT DIMENSION IN DISSIPATIVE MEDIUM

($\mu=4\pi\cdot10^{-7}$ *henry/meter*, $\sigma=0\cdot02$ *mho/meter*)

Field	Frequency (f) Kc/s	Helix Diameter (D) Cm	Wire Diameter (d) mm	Length of linear Antna (L) meter	Helix antenna	Linear antenna
Induction Field	100	1	1	1	$0\cdot5\,(1+\cdot48\times10^{-4})\exp(-0\cdot09r)\,I\sin\theta/r^2$	$0\cdot5\exp(-0\cdot09r)\,I\sin\theta/r^2$
		10	1	1	$0\cdot5\,(1+\cdot48)\exp(-0\cdot09r)\,I\sin\theta/r^2$	$0\cdot5\exp(-0\cdot09r)\,I\sin\theta/r^2$
		10	·5	1	$0\cdot5\,(1+1\cdot92)\exp(-0\cdot09r)\,I\sin\theta/r^2$	$0\cdot5\exp(-0\cdot09r)\,I\sin\theta/r^2$
	500	1	1	1	$1\cdot12\,(1+2\cdot4\times10^{-4})\exp(-0\cdot2r)\,I\sin\theta/r^2$	$1\cdot12\exp(-0\cdot2r)\,I\sin\theta/r^2$
		10	1	1	$1\cdot12\,(1+2\cdot4)\exp(-0\cdot2\,r)\,I\sin\theta/r^2$	$1\cdot12\exp(-0\cdot2\,r)\,I\sin\theta/r^2$
		10	·5	1	$1\cdot12\,(1+9\cdot6)\exp(-0\cdot2r)\,I\sin\theta/r^2$	$1\cdot12\exp(-0\cdot2r)\,I\sin\theta/r^2$
Radiation Field	100	1	1	1	$0\cdot063\,(1+\cdot48\cdot10^{-4})\exp(-0\cdot09r)\,I\sin\theta/r$	$0\cdot063\exp(-0\cdot09r)\,I\sin\theta/r$
		10	1	1	$0\cdot063\,(1+\cdot48)\exp(-0\cdot09r)\,I\sin\theta/r$	$0\cdot063\exp(-0\cdot09r)\,I\sin\theta/r$
		10	·5	1	$0\cdot063\,(1+1\cdot92)\exp(-0\cdot09r)\,I\sin\theta/r$	$0\cdot063\exp(-0\cdot09r)\,I\sin\theta/r$
	500	1	1	1	$0\cdot315\,(1+2\cdot4\cdot10^{-4})\exp(-0\cdot2r)\,I\sin\theta/r$	$0\cdot315\exp(-0\cdot2r)\,I\sin\theta/r$
		10	1	1	$0\cdot315\,(1+2\cdot4)\exp(-0\cdot2r)\,I\sin\theta/r$	$0\cdot315\exp(-0\cdot2r)\,I\sin\theta/r$
		10	·5	1	$0\cdot315\,(1+9\cdot6)\exp(-0\cdot2r)\,I\sin\theta/r$	$0\cdot315\exp(-0\cdot2r)\,I\sin\theta/r$

TABLE 3

FIELD EXPRESSION FOR LINEAR AND HELIX ANTENNAS OF DIFFERENT DIMENSION IN NON-DISSIPATIVE MEDIUM

($\mu = 4\pi \cdot 10^{-7}$ *henry/meter* ; $\sigma = o$)

Field	Frequency (f) Ks/c	Helixe diameter (D) Cm	Wire diameter (d) mm	Lengthof linear antna (L) Meter	Helix Antenna	Linear Antenna
Induction Field	100	1	1	1	$30\,(1+1\cdot35\times10^{-8})\,I\,\sin\theta/r^2$	$30\,I\sin\theta/r^2$
		10	1	1	$30\,(1+1\cdot35\times10^{-4})\,I\,\sin\theta/r^2$	$30\,I\,\sin\theta/r^2$
		10	·5	1	$30\,(1+5\cdot4\times10^{-4})\,I\,\sin\theta/r^2$	$30\,I\,\sin\theta/r^2$
	500	1	1	1	$30\,(1+33\cdot75\times10^{-8})\,I\,\sin\theta/r^2$	$30\,I\,\sin\theta/r^2$
		10	1	1	$30\,(1+33\cdot75\times10^{-4})\,I\,\sin\theta/r^2$	$30\,I\,\sin\theta/r^2$
		10	·5	1	$30\,(1+0\cdot0135)\,I\,\sin\theta/r^2$	$30\,I\,\sin\theta/r^2$
Radiation Feild	100	1	1	1	$0\cdot063\,(1+1\cdot35\times10^{-8})\,I\,\sin\theta/r$	$0\cdot063\,I\,\sin\theta/r$
		10	1	1	$0\cdot063\,(1+1\cdot35\times10^{-4})\,I\,\sin\theta/r$	$0\cdot063\,I\,\sin\theta/r$
		10	·5	1	$0\cdot063\,(1+5\cdot4\times10^{-4})\,I\,\sin\theta/r$	$0\cdot063\,I\,\sin\theta/r$
	500	1	1	1	$0\cdot315\,(1+33\cdot75\times10^{-8})\,I\,\sin\theta/r$	$0\cdot315\,I\,\sin\theta/r$
		10	1	1	$0\cdot315\,(1+33\cdot75\times10^{-4})\,I\,\sin\theta/r$	$0\cdot315\,I\,\sin\theta/r$
		10	·5	1	$0\cdot315\,(1+0\cdot0135)\,I\,\sin\theta/r$	$0\cdot315\,I\sin\theta/r$

It has been observed from Table 1 that for an antenna of given dimension, if frequency be increased, improvement can be obtained. But this increases the attenuation in a dissipative medium. Hence much increase in transmitter frequency is not desirable, and a compromise has to be made. Our preliminary observations show that the frequency band of 300 Kc/s to 500 Kc/s is quite convenient for the purpose. The field strength will of course increase with increase in antenna length. But there is a physical limitation of antenna length at long waves due to the practical consideration of constructing such a large antenna —specially as the antenna is to be burried under ground. The other two parameters *i.e.*, increase in the diameter of the helix and decrease in the diameter of wire can be very easily realised within practical limitations. These two effects further improve the radiation of the helix (due to increased loop radiation) compared to linear antenna of same length. Owing to 'D^4' variation, a slight increase in helix diameter will contribute much. Also the diameter of wire (variation as $1/d^2$) can be reduced to have better effect. Reducing the diameter of wire will cause increase in the number of turns, so long total length of antenna is maintained the same.

As the efficiency of the helical antenna is higher than the linear antenna of same physical length, the relative efficiency can be expressed by a factor R which is a ratio of the effective length of helical antenna to the effective length of linear antenna of same physical length For $L << \lambda$, effective length for the linear antenna is the physical length. The effective lengths for the helical antenna are

$$L_{eff} = L\left(1+\frac{1}{8}\frac{\pi^4 D^4}{\lambda^2 d^2}\right) \quad \text{non dissipative medium,}$$

$$L_{eff} = L\left(1+{}^{1}/_{32}\frac{\pi^2 D^4\,\omega\mu\sigma}{d^2}\right) \quad \text{dissipative medium.}$$

Therefore the values of R for both non-dissipative and dissipative medium are

$$R = 1+\frac{1}{8}\frac{\pi^4 D^4}{\lambda^2 d^2} \quad \text{non-dissipative medium}$$

$$R = 1+\frac{1}{32}\frac{\pi^2 D^4\;\omega\mu\sigma}{d^2} \quad \text{dissipative medium}$$

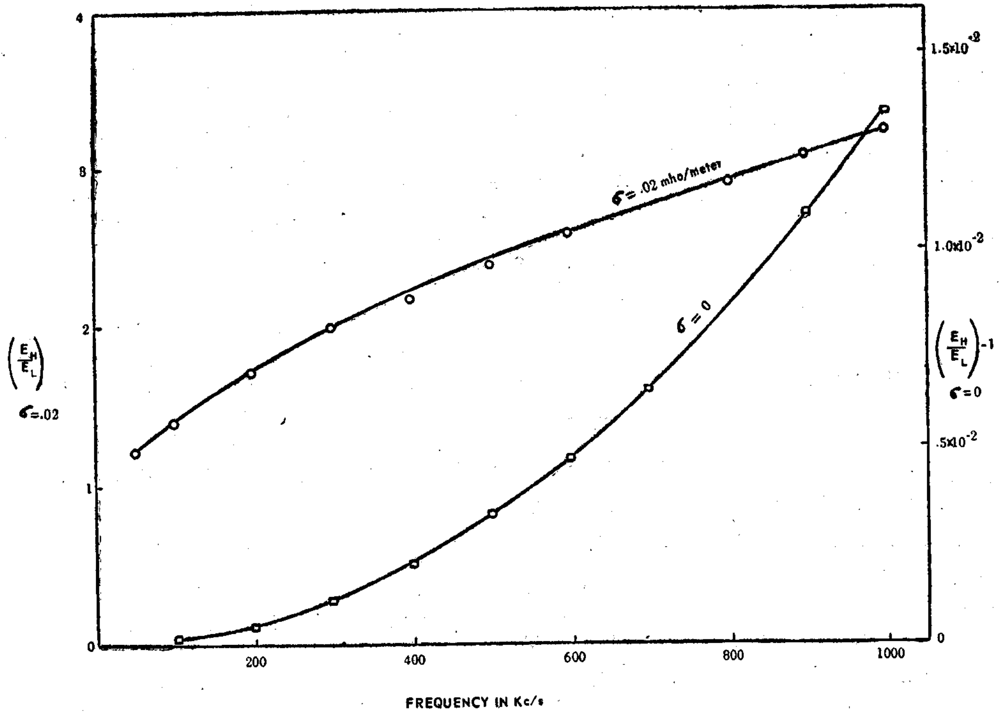

FIG. 5—Variation of the ratio E_H/E_L (radiation field strength of helical antenna of given length/radiation field strength of linear antenna of same length) and $\left(\frac{E_H}{E_L}\right)^{-1}$ with frequency for dissipative and non-dissipative medium respectively. (D=dia of helix=10 cm, d=diameter of wire=1mm, $\mu=4\pi\times10^{-7}$ henry/meter).

The factors arising from the contributions of the loops depend on the parameters of the loop together with the characteristics of the medium.

In (5a) and (5b) the term $\frac{\pi^2 D^4 \omega\mu\sigma}{16 d^2} < 1$ for smaller diameter of the helix and lower frequencies. But from Table 2 it may be observed that it may exceed unity specially at higher frequencies. This happens if the diameter of helix is much increased (resulting in increased contribution from the loops for $D << \lambda$); and the diameter of the winding wire is reduced (which effectively number of loops are increased). The aproximation of expanding and neglecting higher terms containing this factor in the expression $\left(1 + \frac{\pi^2 D^4 \omega\mu\sigma}{16 d^2}\right)^{\frac{1}{2}}$ then fails and the calculated values are not exact. So far the superiority of the helical antenna over the linear antenna of same physical length is concerned this approximation does not disqualify the advantage of the helical antenna and hence may be used in calculation even in these extreme cases, at least for the qualitative assessment of the antenna characteristics. Again, the frequency of interest in Sub-surface Communication is low enough to permit the approximation.

The ralative radiation field strength of the helical antenna with respect to a linear antenna is plotted (Fig. 5) to show the variation of field strength (as also the superiority of helical antenna over the linear antenna in terms of field sterength) with frequency. The relative value is found to increase with increasing frequency within limits, because the response of the loops (so long $D << \lambda$) will improve with frequency.

It may be noted that all the above calculations have been based on a uniform earth characteristics. In practic the earth characteristics may differ in the path of propagatione, and the average value has to be taken. Also, there will be some exrtra loss in energy due to scattering, etc. at the irregularities and interface of earth of different characteristics.

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