LINEAR RADIATORS in NEAR ZONE

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Abstract. The mutual effect of symmetrical electric dipoles located in the near zone of each other is considered. Input impedances, currents and fields of radiators, assuming that theirs feed points are in a horizontal straight line, are calculated. Calculations are based on the theory of folded dipoles. The structure in question is shown to be equivalent to superposition of two basic structures: a two-wire long line and a monopole with a stepped variation of equivalent radius. This model is used to describe the previously proposed compensation method, according with which the radiators' fields cancel each other in some point in the near zone, and the weak field region (a "dark spot") arises around this point.

Аннотация. Рассмотрено взаимное влияние симметричных электрических вибраторов, расположенных в ближней зоне друг друга. Вычислены входные сопротивления, токи и поля излучателей, при условии, что их точки питания лежат на горизонтальной прямой. Расчёты основаны на теории петлевых вибраторов. Показано, что рассматриваемая схема эквивалентна суперпозиции двух базисных структур: двухпроводной длинной линии и монополя со ступенчато изменяющимся по высоте эквивалентным радиусом. Эта модель применена к ранее предложенному методу компенсации, в соответствии с которым поля излучателей взаимно уничтожают друг друга в некоторой точке ближней зоны, а вокруг неё возникает область слабого поля («тёмное пятно»).

Introduction

The question of transmitting antenna near field pattern is of great importance, when in the vicinity of the antenna there is a body, sensitive to electromagnetic (EM) fields that should be protected from EM radiation without shielding it from the external space. Such situation exists in the EM compatibility problems and when people and animals must be protected from EM irradiation.

One problem is that the irradiation of nearby devices can disturb their normal operation, causing un-intentional switching of devices on and off, changes operating conditions, etc. For example, receiving antennas located near the radio transmitter of other systems should not experience significant interference from the transmitter. Frequency diversity not always satisfactorily solves this problem.

Another problem arises because the strong electric field close to power lines and powerful transmitters often creates high anxiety among of the surrounding population. Since the radius of the high field region increases with the wavelength, this problem is especially important in the case of MF waves' radio stations. In the UHF frequency range the near region radius is rather small. However, in the case of personal cellular phones, during a conversation the hand-set unit is placed next to the user's head, and sensitive parts of user's body (brain, eyes, etc.) are exposed to EM irradiation. It is necessary to reduce the amount of the EM energy, absorbed in the head. In today's mobile phones the absorbed energy can reach half of all radiated energy.

Protection against the EM field by screening, i.e. by shading effect, seems to be obvious, but in practice this idea is not applicable. The near field has no ray structure, and hence the shadow formed behind the metal screen can only cover an area approximately equal to the screen size. For example, in order to protect the user's head in cellular telephone, the screen must be much larger than the cross section of the hand-set housing.

For similar reasons, methods using an absorber, i.e. dielectric shield, are not suitable. Methods, using large screens and absorbers, lead to the distortion of the antenna pattern.

The proposed compensation method

The protective action of the proposed compensation method [1] is based on a different principle: mutual suppression of fields created by various radiating elements in a certain area. The compensation method provides a principal opportunity to reduce irradiation of user's organism, especially his head, without distorting the antenna pattern in the horizontal plane. In accordance with this method, in addition to the main radiator (1 in Fig. 1) a second (additional) radiator (2 in Fug. 1) is located in the plane passing through the head centre and the feed point of the main radiator, as shown in Fig. 1.

The second radiator is placed between the head and the main radiator and is exited approximately in anti-phase to it (not exactly anti-phase because of the field's phase progression along the interval between the radiators). Then the radiators' fields will compensate

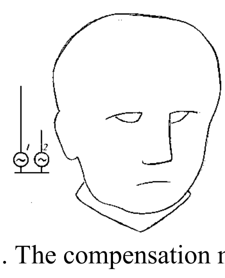

Fig. 1. The compensation method

each other in some point (or along some line) inside the head, and around this point (or line) a zone of a weak field - a dark spot (or a dark belt) will arise.

The dipole moment of the additional radiator must be much less than that of the main radiator, since the near field decreases rapidly (as $1/R^3$, where R is the distance from this radiator). If the currents have substantially different amplitudes, it is sufficient to separate the antennas by a distance of few centimeters (1-2 cm at frequency 1GHz) to create equal field amplitudes at some cancellation point. In this case, the far-zone field differs only slightly from that of the main radiator. “The dark spot” practically has no effect on the far field pattern, since the field near the radiator is not described by a straight lines picture. The field “flows” around the dark spot such that its pattern remains omnidirectional.

Fig. 2 sketches the geometry of the problem. As it can be seen from this Figure, the feed point A_1 of the main radiator and the compensation point A are placed along the horizontal straight line passing through the head center O. We place on this straight line the feed point A_2 of the additional radiator, at a distant h from the main one. Both radiators will be considered to be vertical and with the same length. We assume that the spherical coordinate system origin coincides with point A_1.

Symmetrical dipoles in a near zone

Let each radiator be a symmetrical linear metal dipole of length $2L$, the axis of which is parallel to axis z of a cylindrical coordinate system (ρ, φ, z), and the current along a dipole is distributed by the sinusoidal law

$$J_z = J_A \frac{\sin k(L-|z|)}{\sin kL}, \quad (1)$$

where J_A is the current at the driving point, $k = 2\pi/\lambda$ is the propagation constant, and λ is the wavelength in the surrounding medium. In this case the E_z component of the electric field of the main radiator (radiator 1 in Fig. 2) equals to

$$E_{z1} = -j\frac{30J_{A1}}{\varepsilon_r \sin kL_1}\left[\frac{\exp(-jkR_{11})}{R_{11}} + \frac{\exp(-jkR_{12})}{R_{12}} - 2\cos kL_1 \frac{\exp(-jkR_{10})}{R_{10}}\right],$$

(2)

Here, $R_{11} = \sqrt{(z-L_1)^2 + \rho_1^2}$ is the distance from the observation point M to the upper end of the dipole, $R_{12} = \sqrt{(z+L_1)^2 + \rho_1^2}$ is the distance from point M to the bottom of the dipole, $R_{10} = \sqrt{z^2 + \rho_1^2}$ is the distance

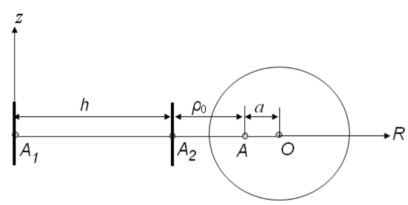

Fig. 2. Radiators’ placement next head

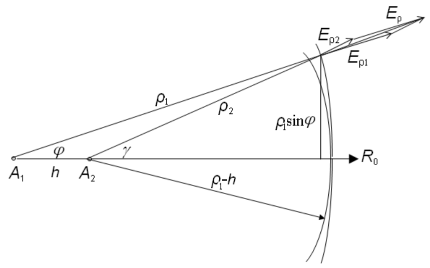

Fig. 3. Two dipoles in cylindrical coordinate system

from point M to the dipole centre. Similarly for the additional radiator (radiator 2 in Fig. 2)

$$E_{z2} = -j\frac{30J_{A2}}{\varepsilon_r \sin kL_2}\left[\frac{\exp(-jkR_{21})}{R_{21}} + \frac{\exp(-jkR_{22})}{R_{22}} - 2\cos kL_2 \frac{\exp(-jkR_{20})}{R_{20}}\right],$$

where

$$R_{21} = \sqrt{(z-L_2)^2 + \rho_2^2}, R_{22} = \sqrt{(z+L_2)^2 + \rho_2^2}, R_{20} = \sqrt{z^2 + \rho_2^2}.$$

Here $\rho_2^2 = \rho_1^2 + h^2 - 2\rho_1 h \cos\varphi$ (Fig. 3). The total vertical field of both radiators is equal to $E_z = E_{z1} + E_{z2}$.

Besides the E_z component each field has also a E_ρ component. For the main radiator

$$E_{\rho 1} = j\frac{30J_{A1}}{\varepsilon_r \rho \sin kL_1}\left[\frac{(z-L)\exp(-jkR_{11})}{R_{11}} + \frac{(z+L)\exp(-jkR_{12})}{R_{12}} - 2z\cos kL_1 \frac{\exp(-jkR_{10})}{R_{10}}\right]$$

and for the additional radiator

$$E_{\rho 2} = j\frac{30J_{A1}}{\varepsilon_r \rho_2 \sin kL_2}\left[\frac{(z-L)\exp(-jkR_{21})}{R_{21}} + \frac{(z+L)\exp(-jkR_{22})}{R_{22}} - 2z\cos kL_1 \frac{\exp(-jkR_{20})}{R_{20}}\right]$$

The square of the total horizontal field of both radiators (see Fig. 3) equals to $E_\rho^2 = E_{\rho 1}^2 + E_{\rho 2}^2 + 2E_{\rho 1}E_{\rho 2}\cos(\gamma - \varphi)$, where $\gamma = \arcsin(\rho \sin\varphi/\rho_2)$. Accordingly the square of the total field is $E^2 = E_z^2 + E_\rho^2$. One can see from these equations that simultaneous compensation of both field components by change of the current J_{A2} is impossible. Since E_z components are usually stronger than E_ρ components, we shall focus on compensation of the E_z components.

If the feed point of the main radiator (Fig. 2) and the compensation point lie at the horizontal straight line, then it is necessary to place the feed point of the additional radiator at the same straight line. In this case the current of the second radiator, neglecting the radiators mutual influence, must be equal to

$$J_{A2} = -J_{A1}\frac{\sin kL_2}{\sin kL_1}\frac{\exp(-jkR_{110})/R_{110} - \cos kL_1 \exp(-jkR_{100})/R_{100}}{\exp(-jkR_{210})/R_{210} - \cos kL_2 \exp(-jk\rho_0)/\rho_0}, \quad (3)$$

where $R_{110} = \sqrt{L_1^2 + (\rho_0 + h)^2}$, $R_{100} = \rho_0 + h$, $R_{210} = \sqrt{L_2^2 + \rho_0^2}$.

The presented equations hold true for a symmetrical electric dipole with an arm length L. For monopoles, the fields’ magnitudes are halved. The expression for E_z of the additional radiator field changes in a similar fashion.

Current and input impedance

As it is well known, the current and the input impedance of a radiator depend on neighboring radiators' currents and mutual impedances. For a system of two radiators, one can write

$$e_1 = J_{A1}Z_{11} + J_{A2}Z_{12},\ e_2 = J_{A1}Z_{21} + J_{A2}Z_{22}. \quad (4)$$

Here e_1 and e_2 are, respectively, the electromotive forces connected in the centers of the first and second radiators, Z_{11} and Z_{22} are the self-impedances of the radiators, Z_{12} and Z_{21} are their mutual impedances.

Each of the two expressions of (4) presents a Kirchhoff equation for a circuit and corresponds to a series connection of circuit elements (Fig. 4). A set of Kirchhoff equations is valid at an arbitrary relative position of radiators. A series circuit is applicable at the dipole arm length $L \le 0{,}4\lambda$.

From (4) in particular follows that

$$J_{A1} = \frac{e_1Z_{22} - e_2Z_{12}}{Z_{11}Z_{22} - Z_{12}Z_{21}},\ J_{A2} = \frac{e_2Z_{11} - e_1Z_{21}}{Z_{11}Z_{22} - Z_{12}Z_{21}}. \quad (5)$$

That is, the current in each radiator is the sum of the currents produced by the self generator, as well as the generator of the neighboring radiator (because of mutual coupling between the radiators). The ratio between these currents depends on the mutual coupling size that depends on the radiators' dimensions and location.

Let us calculate the current and the input impedance of the radiator located in the near region of the neighboring radiator. If the emf is connected at the input of the first one, the equivalent circuit is as shown in Fig. 5. The radiators are electric monopoles with finite lengths, R_1 and R_2 are the internal impedances of the generators: R_1 is the output impedance of the first generator; R_2 is the impedance at the second non excited generator input (or at the input of a cable leading to this generator). Generally, $R_1 = R_2 = R$.

The calculation method for a system with two radiators is constructed on the basis of the folded dipole theory (see for example [2]). Let us connect two voltage generators, equal in size $(e_1/2)$ and opposite in direction, in the base of the radiator 1 (at the right side). We also divide the main generator (with emf e_1) into two generators, equal in size and direction.

According to the superposition principle, the current at each point equals to the sum of the currents produced by all generators. Therefore, as shown in Fig. 6, one can divide each circuit of Fig. 4 into two circuits each containing two generators and next calculate and add the currents in each circuit (points *A* and *B*). Let's assume that in the first circuit only anti-phased currents exist. That is, the currents are equal in size and opposite in direction. In the second circuit we assume that only cophased currents exist so that the potentials of points (on both wires) located at the same heights (including the radiators' bases) are identical. The generators' emfs in the antennas' bases of the second circuit must be equal, if the antennas' radiuses are equal. In this manner, the first circuit is an open top-end two-wire line with load $2R$ in the base. The second circuit pertains to a linear radiator (monopole) with a stepped variation of equivalent radius and with impedance $R/2$ between the generator and the ground.

We write for the two-wire line: $e_1 = J_l(Z_l + 2R)$, where J_l is the current in the line base, $Z_l = -jW_l ctgkL_2$ is the input impedance of line, whose length is equal to the length L_2 of the second, shorter radiator, and the wave impedance is $W_l = 120\ln(b/a)$. Here b is the distance between the wires, $2a$ is the diameter of each wire. The current at point *A* equals to $J_{A1l} = e_1/(-jW_l ctgkL_2 + 2R) = e_1Y_1$, the current at point *B* is $J_{B1l} = -e_1Y_1$, where $Y_1 = 1/(-jW_l ctgkL_2 + 2R)$.

For the monopole we write: $e_1/2 = J_r(Z_r + R/2)$, where J_r is the current in the monopole base, $Z_r = Z_m(L_1, a_e)$ is the input impedance of monopole, which length is equal to the length L_1 of the first radiator, and a_e is its equivalent radius, which is equal to a at the upper monopole section $(L_2 \le z \le L_1)$ and to $\sqrt{ab}$ at the lower monopole section $(0 \le z \le L_2)$. The currents in points *A* and *B* are the same and equal to

$$J_{A1r} = J_{B1r} = e_1/(4Z_r + 2R) = e_1Y_2,$$

where $Y_2 = 1/[4Z_m(L_1, a_e) + 2R]$.

So, if emf e_1 is connected in the first radiator input, the current in its base equals to

$$J_{11} = e_1(Y_1 + Y_2), \quad (6)$$

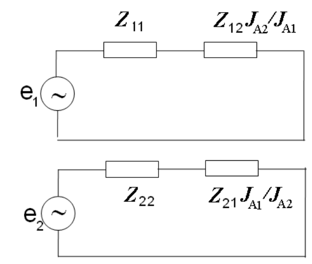

Fig. 4. The equivalent circuit of two coupled radiators

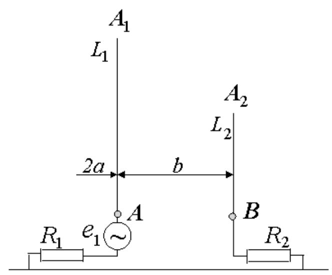

Fig. 5. Two radiators in a near region

the current in the second radiator base is

$$J_{21} = e_1\left(-Y_1 + Y_2\right). \tag{7}$$

If emf e_2 is connected in the second radiator input, then similarly to previous the current in the first radiator base equals to

$$J_{12} = e_2\left(-Y_1 + Y_2\right), \tag{8}$$

the current in the second radiator base is

$$J_{22} = e_2\left(Y_1 + Y_2\right). \tag{9}$$

According to superposition principle at the connection emf in the both radiators inputs

$$J_{A1} = J_{11} + J_{12} = (e_1 - e_2)Y_1 + (e_1 + e_2)Y_2,$$
$$J_{A2} = (e_2 - e_1)Y_1 + (e_1 + e_2)Y_2.$$

The input admittances of the radiators are

$$Y_{A1} = \frac{J_{A1}}{e_1} = Y_1 + Y_2 + \frac{e_2}{e_1}\left(Y_2 - Y_1\right),$$
$$Y_{A2} = \frac{J_{A2}}{e_2} = Y_1 + Y_2 + \frac{e_1}{e_2}\left(Y_2 - Y_1\right). \tag{10}$$

In order to determine the self and the mutual impedances of the radiators (with equal wire radiuses), we compare expressions (6)-(9) with expressions (5). Considering that $J_{11} = \frac{e_1 Z_{22}}{Z_{11}Z_{22} - Z_{12}^2}$, $J_{21} = \frac{-e_1 Z_{12}}{Z_{11}Z_{22} - Z_{12}^2}$, $J_{12} = \frac{-e_2 Z_{12}}{Z_{11}Z_{22} - Z_{12}^2}$, $J_{22} = \frac{e_2 Z_{11}}{Z_{11}Z_{22} - Z_{12}^2}$, we obtain:

$$Z_{11} = Z_{22},\quad Y_1 + Y_2 = \frac{Z_{11}}{Z_{11}^2 - Z_{12}^2},\quad Y_1 - Y_2 = \frac{Z_{12}}{Z_{11}^2 - Z_{12}^2}.$$

Adding and subtracting left and right parts of last two expressions, we find: $2Y_1 = \frac{1}{Z_{11} - Z_{12}}$, $2Y_2 = \frac{1}{Z_{11} + Z_{12}}$, that is $Z_{11} + Z_{12} = \frac{1}{2Y_2}$, $Z_{11} - Z_{12} = \frac{1}{2Y_1}$, and consequently

$$Z_{11} = Z_{22} = \frac{1}{4}\left(\frac{1}{Y_1} + \frac{1}{Y_2}\right) = Z_m\left(L_1, a_e\right) - j\frac{W_l}{4}ctgkL_2 + R,$$
$$Z_{12} = \frac{1}{4}\left(\frac{1}{Y_1} - \frac{1}{Y_2}\right) = -Z_m\left(L_1, a_e\right) - j\frac{W_l}{4}ctgkL_2.$$

The obtained results are surprising because from the physical point of view the first radiator is a thin monopole with arm length L and wire radius a rather than a_e. The second item in the expression for Z_{11} corresponds to a two-wire line, and hence the second

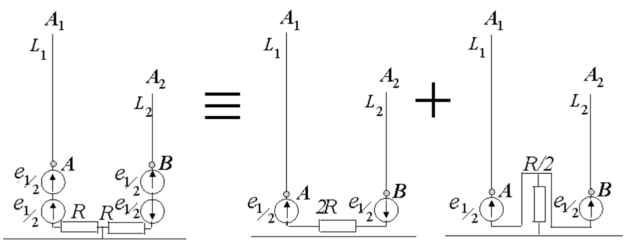

Fig. 6. To a calculation of two radiators in a near region

wire doesn't connect to the first radiator.

Since the second radiator wire is located close to the first wire, at a small distance compared to wavelength, then its effect is similar to connection of some load in the first wire, for example connection of a reactance or a horizontal wire segment. That is the second wire is a concurrent part of the first radiator. A similar approach is valid for the second radiator and for the mutual coupling between them.

Radiators' fields

Mutual effects between near located radiators lead to current redistribution along each of them. For example, the cophased and the anti-phased currents of the first radiator are

$$J_{A1S}(z) = J_{A1S}(0)\frac{\sin k\left(L_1 - |z|\right)}{\sin kL_1},\quad J_{A1P}(z) = J_{A1P}(0)\frac{\sin k\left(L_2 - |z|\right)}{\sin kL_2}.$$

Here $J_{A1S}(0) = (e_1 + e_2)Y_2$, $J_{A1P}(0) = (e_1 - e_2)Y_1$. Then the vertical component of the first radiator field is equal to $E_{z1} = E_{z1S}(z) + E_{z1P}(z)$,

where

$$E_{z1S}(z) = -j\frac{15(e_1 + e_2)Y_2}{\varepsilon_r}F_{11},\quad E_{z1P}(z) = -j\frac{15(e_1 - e_2)Y_1}{\varepsilon_r}F_{21},$$

at that

$$F_{im} = \frac{1}{\sin kL_i}\left(\frac{e^{-jkR_{im1}}}{R_{im1}} + \frac{e^{-jkR_{im2}}}{R_{im2}} - 2\cos kL_i\frac{e^{-jkR_{0m}}}{R_{0m}}\right), \tag{11}$$

where $R_{im1} = \sqrt{\left(z_i - L_i\right)^2 + \rho_m^2}$, $R_{im2} = \sqrt{\left(z_i + L_i\right)^2 + \rho_m^2}$, $R_{0m} = \sqrt{z_i^2 + \rho_m^2}$. One can write the similar formulas for second radiator.

In order for the total radiators' field in the compensation point to vanish, the ratio of currents in the radiators bases must be equal to

$$\frac{J_{A2}}{J_{A1}} = -\frac{F_{110} + F_{210}}{F_{110} - F_{210} + 2F_{220}}. \tag{12}$$

This expression takes into account the mutual coupling between near located radiators.

Conclusions

We have presented a simple model for description of linear radiators located inside the near field regions of each other. This model is applied to the novel compensation method used for creation of a weak field area. The results show that the compensation method is promising for reducing undesired EM radiation at certain region in the vicinity of the radiators. It is expedient to use the folded dipoles theory for analyze of results.

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