Propagation Along a Braided Coaxial Cable in a Circular Tunnel

JAMES R. WAIT, FELLOW, IEEE, AND DAVID A. HILL, MEMBER, IEEE

***Abstract*—The modes of propagation along a coaxial structure contained within a circular tunnel are considered. The primary objective is to develop an approximate impedance boundary condition at the outer surface of the shielded cable that can be used in previously developed formalisms for axial conductors in tunnels. It is assumed that the metal braid can be characterized by a surface-transfer impedance. We also account for the possibility that a lossy film exists on the outer surface of the dielectric jacket of the cable.**

INTRODUCTION

THERE IS A NEED to understand how electromagnetic waves propagate in tunnels if improved communication systems in mines are to be developed in a logical fashion. One approach now being developed is to exploit the leaky-feeder principle [1]. In this method, which can be described as continuous-access communications, the signals are guided by transmission lines or shielded conductors. The principal idea is that energy can be coupled into and out of the transmission channel by antennas that only need be in the general vicinity of the two-wire line or cable.

In developing the theory of mode propagation along axial conducting structures in cylindrical tunnels, we need to apply an impedance boundary condition at the outer surface of the guiding structure. In the case of a bare metallic wire, the appropriate expression to use is the series impedance Z_i defined as follows: $Z_i = E_a/I$ where $I = \oint H_t \, ds$. Here, E_a is the average axial field at the surface of the conductor, while H_t is the azimuthal magnetic field. For a thin circular wire of radius a with electromagnetic constants σ_w, ϵ_w, and μ_w, we can use the following argument.

FORMULATION FOR IMPEDANCE OF AN INNER CONDUCTOR

A cylindrical coordinate system (ρ, ϕ, z) is adopted such that the surface of the wire is $\rho = a$. If the external fields are now locally uniform, we can neglect the azimuthal variation around the wire and consider only the axial current flow. For fields that vary as $\exp(-\Gamma z + i\omega t)$ where Γ is a propagation constant, the Hertz vector has only a z component Π_w. Thus, within the wire $\rho \leq a$, we can write

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The authors are with the Institute for Telecommunication Sciences, Office of Telecommunications, U.S. Department of Commerce, Boulder, Colo. 80302.

$$E_z = (k_w^2 + \partial^2/\partial z^2)\Pi_w = (k_w^2 + \Gamma^2)\Pi_w$$
$$H_\phi = -(\sigma_w + i\epsilon_w\omega)\,\partial\Pi_w/\partial\rho \tag{1}$$

where

$$ik_w = [(i\mu_w\omega)(\sigma_w + i\epsilon_w\omega)]^{1/2}.$$

The appropriate form of the solution for Π_w is the modified Bessel function $I_0[i(k_w^2 + \Gamma^2)^{1/2}\rho]$ times a constant factor. Thus according to our basic definition

$$Z_i = E_z/(2\pi\rho H_\phi)\,|_{\rho=a} \tag{2}$$

or

$$Z_i = \frac{i(k_w^2 + \Gamma^2)^{1/2}}{2\pi(\sigma_w + i\epsilon_w\omega)a}\,\frac{I_0[i(k_w^2 + \Gamma^2)^{1/2}a]}{I_1[i(k_w^2 + \Gamma^2)^{1/2}a]}. \tag{3}$$

In the usual case where $|\Gamma^2| \ll |k_w^2|$ this simplifies to

$$Z_i \simeq \frac{(i\mu_w\omega)^{1/2}}{2\pi(\sigma_w + i\epsilon_w\omega)^{1/2}a}\,\frac{I_0(ik_w a)}{I_1(ik_w a)}. \tag{4}$$

In the dc limit (i.e., $\omega \to 0$) we see that Z_i reduces to the expected form $(\pi a^2\sigma_w)^{-1}$.

In previous papers on this subject, we have used the boundary condition $E_z = IZ_i$ to apply to the surface of the thin wire even when the external region is complex. Two examples were axial conductors in a circular tunnel [2] and an axial conductor in a rectangular tunnel [3]. The justification for this type of boundary condition is that the external fields are locally uniform. Thus, on physical grounds, we expect the results to be valid when the wire radius is small compared with the distance to neighborhood surfaces and when the quantity $|\beta a| \ll 1$. Here β is the effective transverse wavenumber in the external region. There is some experimental support for this analytical approach to such problems [4].

EXTENSION TO BRAIDED SHIELD, DIELECTRIC LAYERS, AND OUTER LOSSY FILM

We now wish to extend this series-impedance concept to the case where the axial wire conductor is covered by a layer of perfect insulation of radius b with dielectric constant ϵ and free-space permeability μ_0. To allow for the presence of a metal braided shield, we assume that there is a thin uniform sheath of radius b with a designated transfer impedance Z_T in ohms/meter. Surrounding this, we have a coating whose dielectric constant is ϵ_c; it is also assumed lossless and a has a free-space permeability. Finally, to allow for a layer of mine dust or conducting fluid, we assume there is a thin outer layer of conductive material with a transfer impedance Z_L. This situation is illustrated in Fig. 1 where the cross section of this braided coaxial cable with lossy outer sheath is depicted.

The situation is admittedly simplified, particularly with regard to the thin uniform sheath representation of the braided shield. In fact, the nonuniformities of the braid and random perforations of the shield will play an important role in the performance of an actual system. However, for present purposes we will consider just a uniform or smoothed-out version of the braid. We can rely on other work [5] to give us an estimate on the expected value of the transfer impedance Z_T. In a similar fashion, we justify the use of the transfer impedance Z_L for the external lossy film. The appropriate value here can be estimated from the approximate formula $Z_L \simeq (2\pi c\sigma d)^{-1}$ Ω/m, where σd is the conductivity–thickness product of the lossy film. Such an easily recognizable expression is justified when d is small compared with the electric skin depth $(2/\sigma\mu\omega)^{1/2}$ of the film material, and also d should be small compared with the radius c.

The brief derivation given below for the effective series impedance follows the classical approach for cylindrical structures [6], [7].

The axial electric field and the azimuthal magnetic field for the three regions thus have the following form for fields that vary as exp $(i\omega t - \Gamma z)$:

$$\left.\begin{aligned} E_z &= (k^2 + \Gamma^2)\Pi = \beta^2\Pi \\ H_\phi &= -i\epsilon\omega\partial\Pi/\partial\rho \end{aligned}\right\} \quad \text{for} \quad a < \rho < b \tag{5}$$

$$\left.\begin{aligned} E_z &= (k_c^2 + \Gamma^2)\Pi_c = \beta_c^2\Pi_c \\ H_\phi &= -i\epsilon_c\omega\partial\Pi_c/\partial\rho \end{aligned}\right\} \quad \text{for} \quad b < \rho < c \tag{6}$$

and

$$\left.\begin{aligned} E_z &= (k_0^2 + \Gamma^2)\Pi_0 = \beta_0^2\Pi_0 \\ H_\phi &= -i\epsilon_0\omega\partial\Pi_0/\partial\rho \end{aligned}\right\} \quad \text{for} \quad \rho > c \tag{7}$$

where Π, Π_c, and Π_0 are the Hertz potentials for the three respective regions. Also β, β_c, and β_0 are the corresponding transverse wavenumbers and they are defined as indicated above. Now in any of the three regions, the Hertz potentials can be written as linear combinations of the Bessel functions J_0 and Y_0 with arguments $\beta\rho$, $\beta_c\rho$, and $\beta_0\rho$, respectively. Then, for example, for the first region we deduce readily that

$$\left.\begin{aligned} E_z &= \beta^2[PJ_0(\beta\rho) + QY_0(\beta\rho)] \\ H_\phi &= i\epsilon\omega\beta[PJ_1(\beta\rho) + QY_1(\beta\rho)] \end{aligned}\right\} \quad \text{for} \quad a < \rho < b \tag{8}$$

and

$$\left.\begin{aligned} E_{cz} &= \beta_c^2[MJ_0(\beta_c\rho) + NY_0(\beta_c\rho)] \\ H_{c\phi} &= i\epsilon_c\omega\beta_c[MJ_1(\beta_c\rho) + NY_1(\beta_c\rho)] \end{aligned}\right\} \quad \text{for} \quad b < \rho < c. \tag{9}$$

Here P, Q, M, and N are constants yet to be determined. We have similar expressions in the external region, but here we utilize the fact that the "scattered" field is an outgoing wave and thus the solution for Π_0 is characterized by a linear combination of J_0 and $H_0^{(2)}$ where the latter is the Hankel function of the second kind. Thus we can write

$$\left.\begin{aligned} E_{0z} &= A[J_0(\beta_0\rho) + R_0H_0^{(2)}(\beta_0\rho)] \\ H_{0\phi} &= Ai\epsilon_0\omega\beta_0^{-1}[J_1(\beta_0\rho) + R_0H_1^{(2)}(\beta_0\rho)] \end{aligned}\right\} \quad \text{for} \quad \rho > c. \tag{10}$$

Here A can be regarded as the strength of the axial electric field of the "primary" wave at $\rho = 0$ that would exist if the structure were not present. The coefficient R_0 then determines the relative strength of the scattered field. Obviously, if the parameter $|\beta_0 c|$ is not sufficiently small, we would need to include Bessel functions of order m and the factor exp $(im\phi)$ in the solutions for all the Hertz potentials.

The boundary conditions for the problem can now be stated succintly as follows:

$$E_z = 2\pi a Z_i H_\phi \quad \text{at} \quad \rho = a \tag{i}$$

$$E_z = E_{cz} \quad \text{at} \quad \rho = b \tag{ii}$$

$$H_\phi - H_{c\phi} = -(2\pi b Z_T)^{-1}E_z \quad \text{at} \quad \rho = b \tag{iii}$$

$$E_{cz} = E_{0z} \quad \text{at} \quad \rho = c \tag{iv}$$

$$H_{c\phi} - H_{0\phi} = -(2\pi c Z_L)^{-1}E_z \quad \text{at} \quad \rho = c. \tag{v}$$

Here (i) is the impedance boundary condition that we impose at the surface of the inner conductor. It is an "exact" condition if we use (3), but for practical purposes, Z_i can be taken to be independent of Γ so that (4) is adequate. Conditions (ii) and (iv) indicate that the axial electric field is effectively continuous through the braid and the lossy-film layer. This is a consequence of the assumed thinness of these layers (i.e., the thicknesses are small compared with the effective wavelength in the respective media).

From boundary condition (i) above, we easily deduce that

$$Q/P = R = -\frac{[J_0(\beta a) - i2\pi akZ_i(\beta\eta)^{-1}J_1(\beta a)]}{[Y_0(\beta a) - i2\pi akZ_i(\beta\eta)^{-1}Y_1(\beta a)]} \tag{11}$$

where $\eta = \mu\omega/k = (\mu/\epsilon)^{1/2}$. Similarly, from (ii) we find

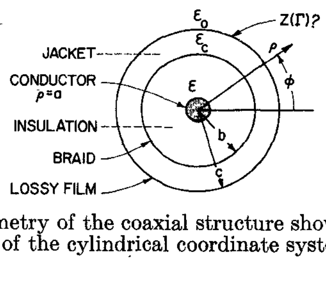

Fig. 1. The geometry of the coaxial structure showing the orientation of the cylindrical coordinate system.

that

$$P = M\frac{\beta_c^2}{\beta^2}\frac{J_0(\beta_c b) + R_c Y_0(\beta_c b)}{J_0(\beta b) + R Y_0(\beta b)} \tag{12}$$

where $R_c = N/M$. Then an application of (iii) yields

$$\begin{aligned} R_c = &\Bigg\{\beta^2\left(\frac{i\beta_c k_c}{\eta_c}J_1(\beta_c b) - \frac{\beta_c^2 J_0(\beta_c b)}{2\pi b Z_T}\right) \times (J_0(\beta b) \\ &+ R Y_0(\beta b)) - \frac{i\beta k}{\eta}\beta_c^2 J_0(\beta_c b)[J_1(\beta b) + R Y_1(\beta b)]\Bigg\} \\ &\times \Bigg\{-\beta^2\left(\frac{i\beta_c k_c}{\eta_c}Y_1(\beta_c b) - \frac{\beta_c^2 Y_0(\beta_c b)}{2\pi b Z_T}\right) \\ &\times (J_0(\beta b) + R Y_0(\beta b)) \\ &+ \frac{i\beta k}{\eta}\beta_c^2 Y_0(\beta_c b)[J_1(\beta b) + R Y_1(\beta b)]\Bigg\}^{-1}. \end{aligned} \tag{13}$$

An application of (iv) tells us that $M\beta_c^2[J_0(\beta_c c) + R_c Y_0(\beta_c c)] = A[J_0(\beta_0 c) + R_0 H_0^{(2)}(\beta_0 c)]$. Combining this with (v) yields

$$R_0 = -\frac{\left[\frac{ik_0}{\eta_0}J_1(\beta_0 c) - \frac{\beta_0 J_0(\beta_0 c)}{2\pi c Z_L} - \frac{ik_c}{\eta_c}\frac{\beta_0}{\beta_c}\frac{J_1(\beta_c c) + R_c Y_1(\beta_c c)}{J_0(\beta_c c) + R_c Y_0(\beta_c c)}J_0(\beta_0 c)\right]}{\left[\frac{ik_0}{\eta_0}H_1^{(2)}(\beta_0 c) - \frac{\beta_0 H_0^{(2)}(\beta_0 c)}{2\pi c Z_L} - \frac{ik_c}{\eta_c}\frac{\beta_0}{\beta_c}\frac{J_1(\beta_c c) + R_c Y_1(\beta_c c)}{J_0(\beta_c c) + R_c Y_0(\beta_c c)}H_0^{(2)}(\beta_0 c)\right]}. \tag{14}$$

Now the desired result is the effective series impedance defined by

$$\begin{aligned} Z(\Gamma) &= \frac{E_{0z}}{2\pi c H_{0\phi}} \quad \text{at} \quad \rho = c \\ &= \frac{\beta_0\eta_0[J_0(\beta_0 c) + R_0 H_0^{(2)}(\beta_0 c)]}{2\pi c i k_0[J_1(\beta_0 c) + R_0 H_1^{(2)}(\beta_0 c)]}. \end{aligned} \tag{15}$$

QUASI-STATIC LIMITING FORM FOR $Z(\Gamma)$

The resulting expression for $Z(\Gamma)$ that is a function of the axial propagation constant Γ is rather involved. Fortunately, considerable simplification ensues if we consider the case where the arguments of the Bessel functions are sufficiently small that only the leading terms in their power-series expansions need be retained. In this connection it might be mentioned that in some important cases βc may not be "small" even when $\beta_0 c$ is small. For example, this could occur when $\Gamma \sim ik_0$, in which case $\beta_0 c$ is small even though $k_0 a$ may be comparable with one. However, in the quasi-static limit that we discuss below, it will be assumed that all the arguments are small.

To provide insight into the quasi-static limiting forms, we write out the field expressions that correspond to (8)–(10). Here we utilize the small-argument approximations $J_0(x) \to 1$, $J_1(x) \to x/2 \to 0$, $Y_0(x) \to (2/\pi)\ \ln 0.89x$, and $Y_1(x) \to -2/(\pi x)$. Thus

$$\left.\begin{aligned} E_z &\simeq \beta^2[P + (2/\pi)Q \ln 0.89\beta\rho] \\ H_\phi &\simeq -(2/\pi)i\epsilon\omega Q/\rho \end{aligned}\right\} a < \rho < b \tag{16}$$

$$\left.\begin{aligned} E_{cz} &\simeq \beta_c^2[M + (2/\pi)N \ln 0.89\beta_c\rho] \\ H_{c\phi} &\simeq -(2/\pi)i\epsilon_c\omega N/\rho \end{aligned}\right\} b < \rho < c \tag{17}$$

and

$$\left.\begin{aligned} E_{0z} &\simeq A[1 + R(1 - (i2/\pi) \ln 0.89\beta_0\rho] \\ H_{0\phi} &\simeq -A(2/\pi)i\epsilon_0\omega R/\rho \end{aligned}\right\} c < \rho < \hat{\rho}. \tag{18}$$

Here $\hat{\rho}$ is any value greater than c chosen such that $|\beta_0\hat{\rho}| \ll 1$. It is useful to note that in each region $H_\phi \times \rho$ is a constant in this limiting situation.

As an exercise, we can now apply boundary conditions (i)–(v) and get explicit quasi-static forms for the coefficients, or we can insert the small-argument approximations in the Bessel functions in (11)–(15). In either case, we obtain the following formula for the effective series impedance:

$$Z(\Gamma) \simeq \frac{Z_L(Z_c + Z_b)}{Z_L + Z_c + Z_b} \tag{19}$$

where

$$Z_b = \frac{Z_T(Z' + Z_i)}{Z_T + Z' + Z_i} \tag{20}$$

where

$$Z' = -\frac{k^2 + \Gamma^2}{2\pi i\epsilon\omega}\ln(b/a) \tag{21}$$

and

$$Z_c = -\frac{k_c^2 + \Gamma^2}{2\pi i\epsilon_c\omega}\ln(c/b). \tag{22}$$

The equivalent circuit for this situation is the ladder network shown in Fig. 2. The terminating element Z_i is the impedance of the inner conductor while the shunt elements Z_T and Z_L are the transfer impedances of the braid and

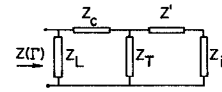

Fig. 2. The equivalent ladder network that yields the effective series impedance of the cable in the quasi-static approximation.

the external lossy film. The series elements Z_c and Z' can be identified as short sections of transmission lines whose properties depend on Γ. We stress that this quasi-static equivalent circuit is only valid when all the Bessel-function arguments are small compared with one. The expression for the series impedance given by (15) is not so restricted.

APPLICATION TO CIRCULAR-TUNNEL MODEL

We now consider the circular-waveguide model of a mine tunnel. The situation is depicted in Fig. 3 where the tunnel radius is a_0 while the cable is located at a distance ρ_0 from the tunnel axis. In an earlier paper [2], we determined the axial propagation constants of the permitted modes of the structure that satisfied both the impedance boundary conditions at the waveguide wall and at the surface of an axial conductor whose series impedance is specified. In the present case, the axial structure in the waveguide is the braided coaxial that we discussed previously. The impedance boundary condition is to be applied at the outer surface of the lossy-film coating whose radius is c. As indicated in Fig. 3, the distance of the cable from the tunnel wall is $a_0 - \rho_0$. In order for the solution to be valid, c should be small compared with $a_0 - \rho_0$.

As in the earlier paper, the homogeneous medium bounding the tunnel walls has a conductivity σ_e and a permittivity ϵ_e. In what follows, we choose $\sigma_e = 10^{-2}$ mho/m, $\epsilon_e = 10\epsilon_0$, and $a_0 = 2$ m. The interior region of the waveguide is free space, except at the braided coaxial. The dimensions of the latter, with reference to Fig. 1, are taken as follows: $a = 1.5$ mm, $b = 10$ mm, and $c = 11.5$ mm. Also, for purposes of illustration, we take the transfer impedance Z_T of the braid to be $i\omega L$ where $L = 40$ nH/m. This corresponds to the FONT cable developed by Fontaine *et al.* [5].

The relative dielectric constant ϵ/ϵ_0 of the insulator is taken to be 2.5 corresponding to polystyrene, for example. For an optimum system, we might have chosen a lower value but, for present purposes, this is not important. For the outer coating, the relative dielectric constant ϵ_c/ϵ_0 is taken to be 3.0 corresponding to typical jacket material. To allow for the presence of the outer lossy film, we choose the transfer impedance $Z_L = [2\pi c(\sigma d)]^{-1}$ where the conductivity–thickness product is to be specified. For example, a conducting fluid layer with $\sigma = 10$ mho/m whose thickness $d = 1$ mm leads to $(\sigma d) = 10^{-2}$ mho. As indicated by Rawat and Beal [8], the presence of such lossy films in realistic mine environments should be expected.

Using the above analytical machinery, we illustrate some results for the dominant modes of the braided cable located in the cylindrical structure. There are two important modes that we call the monofilar and bifilar modes. The first of these is similar to the situation treated before where we have a bare uncoated wire in the waveguide [2], [3]. In that case, the return current flows along the walls of the cylindrical waveguide. The second type is analogous to the currents flowing in a two-wire transmission line and the characteristic of this bifilar mode is almost independent of the waveguide walls. For the braided coaxial structure, this particular mode is the conventional one since the currents in the center conductor and braid are approximately equal but with opposite signs.

In Fig. 4, we show the attenuation rate (in nepers/meter) for the monofilar mode as a function of frequency from 0.2 to 200 MHz. Several values of ρ_0/a_0 are indicated as are two values of (σd). Also for this example, the conductivity σ_w of the center conductor is taken to be 10^7 mho/m, but for this mode, the attenuation is not critically dependent on σ_w. Also, except for higher frequencies, the attenuation rate is not influenced appreciably by (σd) for values even as high as 10^{-1} mho. As expected, of course, the attenuation rate for this monofilar mode increases as the coaxial is moved toward the wall. Note that $\rho_0/a_0 = 0.9$ corresponds to a distance $s - s_0 = 20$ cm ~ 8 in from the wall.

In Fig. 5 we show some corresponding results for the bifilar or coaxial-type mode. Since there is a strong dependence on the conductivity σ_w of the inner conductor, three different values are selected. The highest value $\sigma_w \sim 5.7 \times 10^7$ mho/m corresponds to copper. In this case, we also see that the results depend somewhat on the (σd) values, particularly at the upper frequencies. The

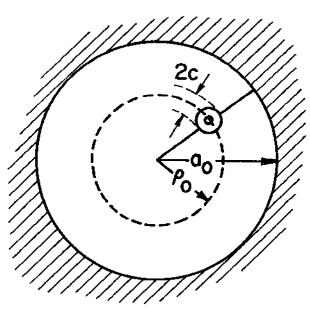

Fig. 3. The circular-waveguide model showing the location of the cable.

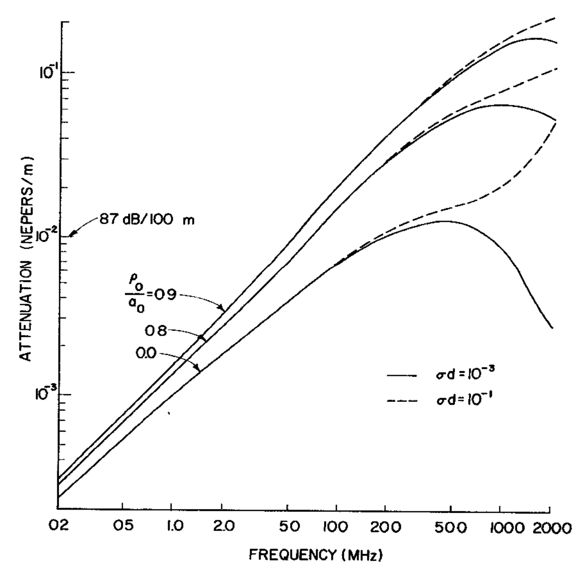

Fig. 4. The attenuation rate of the monofilar mode as a function of frequency. $a_0 = 2$ m.

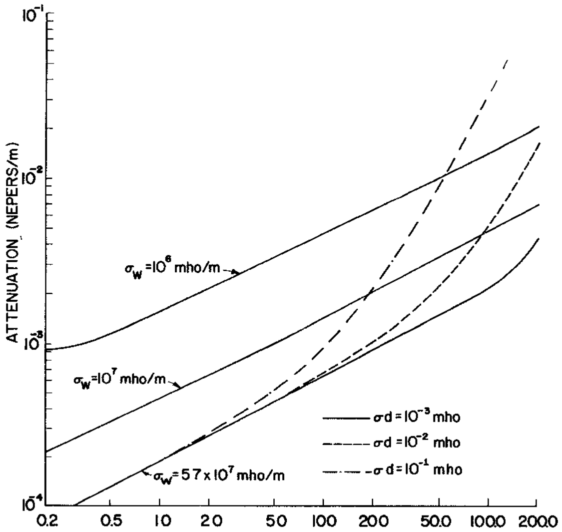

Fig. 5. The attenuation rate of the bifilar mode illustrating the dependence on the conductivity of the inner conductor and the effect of the external lossy film. $\epsilon = 2.5\epsilon_0$: $\epsilon_c = 3.0\epsilon_0$: $L = 40$ nH/m.

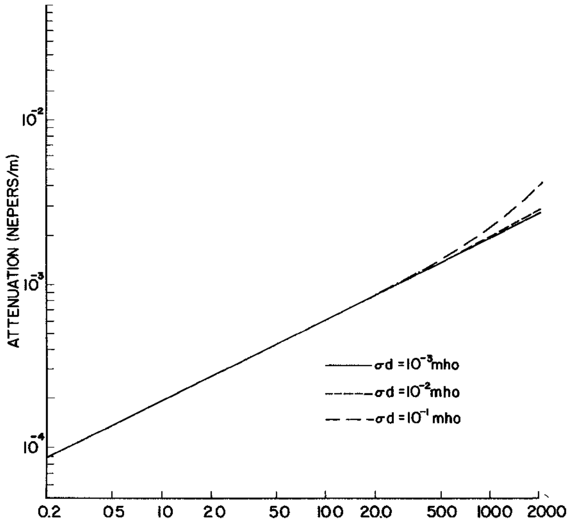

Fig. 6. The attenuation rate of the bifilar mode for a smaller value of the surface transfer impedance. $\sigma_w = 5.7 \times 10^7$ mho/m: $L = 4$ nH/m: $\epsilon = 2.5\epsilon_0$: $\epsilon_c = 3.0\epsilon_0$.

presence of the lossy film increases the attenuation of the bifilar mode for the range of frequencies and σd parameter considered in this figure. Actually, for the curves in Fig. 5 we have chosen $\rho_0/a_0 = 0.8$, but the results for this bifilar mode hardly depend at all on the value of ρ_0/a_0. In fact, the curves would be indistinguishable for $0 \leq \rho_0/a_0 \leq 0.9$.

In Fig. 6 we show the corresponding bifilar mode attenuation for the copper inner conductor. Here we choose the transfer inductance $L = 4$ nH/m that is a factor of 10 lower than before. The important point here is that the attenuation rate depends only slightly on the conductivity–thickness product (σd) of the outer lossy film. Thus, while high values of L are desirable from the standpoint of coupling to the desired bifilar mode, we can expect a greater susceptibility to the presence of lossy fluid or mine-dust layers on the outer jacket.

CONCLUDING REMARKS

The present results are believed to be a useful basis for the design of leaky-feeder communications systems that employ shielded cables in mine tunnels. The analytical method can be applied equally well to rectangular tunnels [9]. The effect of axial nonuniformities in the guiding structures needs to be considered if we are to utilize fully the capabilities of both the monofilar and the bifilar modes.

In principle, the method could be applied at much higher frequencies for single dielectric-coated conductors where the dominant mode would be a surface wave [10]–[12] whose energy is confined to the cable. Several difficulties emerge here. First of all, the assumption of local uniformity of the fields about the cable would need to be removed. Also, the hostile environment in most mine tunnels would produce very high attenuation due to moisture and coal dust. Also, the coupling to the surface-wave line would be not feasible for a roving miner. Nevertheless, we should keep an open mind on the possible relevance of Goubau-type surface-wave lines in mine environments.

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