Letters

On the Attenuation of Monofilar and Bifilar Modes in Mine Tunnels

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Abstract—**The modal equations for both the monofilar and bifilar modes of a two open wire transmission line located in a waveguide model of a rectangular mine tunnel are derived by extending an earlier general analysis. Attenuation curves of both modes in the frequency range 200 kHz–200 MHz are presented for two distinct configurations of the transmission line that may be used in practice. It is demonstrated that the proximity of the lossy tunnel wall tends to increase greatly the attenuation rate for the monofilar modes but has relatively little effect on the bifilar modes.**

INTRODUCTION

Radio communication in mine tunnels can be provided by the free propagation of UHF waves in the tunnel which acts as a natural waveguide at this band of frequencies [1]. It is also possible to use much lower frequencies if a longitudinal conductor is stretched along the tunnel. Such a conductor will support a TEM-like mode, usually referred to as the monofilar mode, which is characterized by a zero cutoff frequency [2]. However, the fields of such a mode are accessible in the whole cross section of the tunnel at the expense of a high-power absorption by the tunnel walls. In order to reduce such loss, a two (or more) wire transmission line (TL) system should be used, whereby a new mode that has antiphased currents in the two wires is created. This mode, which is usually referred to as the bifilar mode, has fields that are concentrated in the near vicinity of the TL and hence suffers relatively low loss.

Attenuation measurements in some Belgium mine tunnels at 27 and 68 MHz affirm the lower attenuation of the bifilar mode relative to that of the monofilar mode [3]. The obviously important requirement of achieving controlled conversion between these two modes has been extensively studied by Delogne [2] and Deryck [4].

A rigorous modal equation for the monofilar mode of a single wire in a rectangular tunnel has recently been obtained by Mahmoud and Wait [5] under some simplifying assumptions concerning the two side walls of the tunnel. Also, extensive numerical results on the properties of this mode have been reported by the author [6]. In the present letter, we extend the analysis in [5] to derive the modal equations of the monofilar and bifilar modes of a two open wire TL inside the rectangular tunnel. Some specific results of the attenuation constants of these modes in a wide range of frequencies are presented.

THE MODAL EQUATIONS

We consider two configurations A and B of the TL as shown in Fig. 1. As in [5], the two side walls of the tunnel are assumed to behave as either perfect electric or perfect magnetic conductors, while the other two walls are taken as generally lossy dielectric media. In both configurations, A and B, we shall adopt the nonrestrictive assumption that $d \gg \rho$ where ρ is the radius of any of the wires. For a particular mode of propagation, all the fields in the guide and the currents in the two wires behave as $\exp(i\omega t - \Gamma z)$ where ω is the angular frequency and Γ is the complex propagation constant of the mode. So, apart from this common term, let the currents in the two wires be given by I_1 and I_2. The boundary condition at the surface of each wire requires that the longitudinal electric field be equal to the current multiplied by the series impedance Z_w per unit length of the wire. These conditions can be put in the convenient forms:

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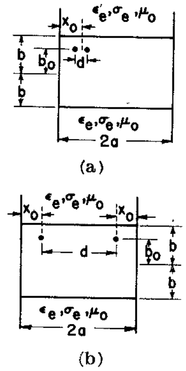

Fig. 1. Two configurations A and B of open wire TL inside a waveguide model of a rectangular tunnel.

$$Z_{s1}(\Gamma)I_1 + Z_m(\Gamma)I_2 = Z_{w1}I_1 \tag{1}$$

$$Z_m(\Gamma)I_1 + Z_{s2}(\Gamma)I_2 = Z_{w2}I_2 \tag{2}$$

where $Z_{s1}(\Gamma)$ is defined as the longitudinal electric field at the surface of the first wire due to a unit current in that wire and a similar definition applies to $Z_{s2}(\Gamma)$. $Z_m(\Gamma)$ is the longitudinal electric field at the surface of one wire due to a unit current in the other wire. These quantities are directly obtainable from (19) and (20) in [5] after the appropriate substitutions for the coordinates of the source and the observation point; e.g., $Z_{s1}(\Gamma)$ and $Z_m(\Gamma)$ for configuration A in Fig. 1 are given by

$$Z_{s1}(\Gamma) = (-i\omega\mu_0/\pi)B(\Gamma) \Big| \begin{array}{l} x_0 \to x_0 - d/2 \\ y_0 \to b + b_0 \\ x \to x_0 - d/2 \\ y \to b + b_0 + \rho \end{array}$$

$$Z_m(\Gamma) = (-i\omega\mu_0/\pi)B(\Gamma) \Big| \begin{array}{l} x_0 \to x_0 - d/2 \\ y_0 \to b + b_0 \\ x \to x_0 + d/2 \\ y \to b + b_0 + \rho \end{array} \tag{3}$$

where $B(\Gamma)$ is given in [5].

By the elimination of I_1 and I_2 in (1) and (2), we obtain the modal equation for the unknown Γ as

$$(Z_{s1}(\Gamma) - Z_{w1})(Z_{s2}(\Gamma) - Z_{w2}) - Z_m^2 = 0. \tag{4}$$

This equation is greatly simplified when the two wires are identical since then, $Z_{w1} = Z_{w2} = Z_w$. Furthermore, we can put $Z_{s1}(\Gamma) \simeq Z_{s2}(\Gamma) = Z_s(\Gamma)$, which is an exact equation for configuration B in Fig. 1 (due to symmetry) and a very good approximation for configuration A since d is much less than the guide width. Under the preceding conditions, equation (4) reduces to two simple equations given by

$$Z_s(\Gamma) + Z_m(\Gamma) - Z_w = 0 \tag{5}$$

and

$$Z_s(\Gamma) - Z_m(\Gamma) - Z_w = 0 \tag{6}$$

where the first equation implies that $I_1 = I_2$ and the second implies that $I_1 = -I_2$. These are the two equations that correspond to the monofilar and the bifilar modes, respectively, and their solutions give the propagation constants of these modes.

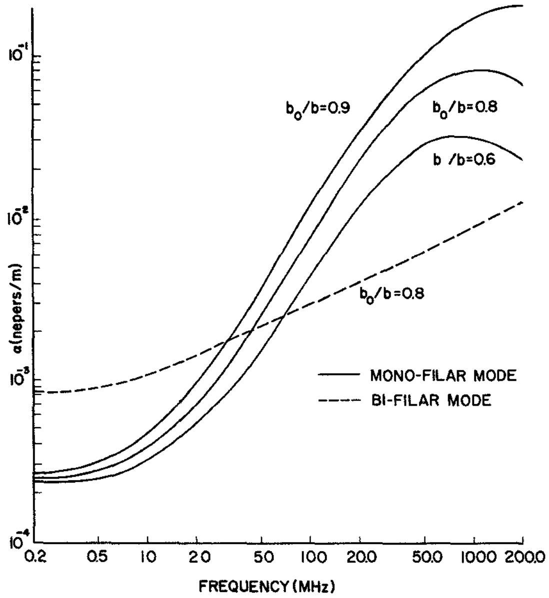

Fig. 2. Attenuation constant of the monofilar and the bifilar modes of configuration A versus frequency for various values of b_0/b. Wire radii $\rho = 1$ mm.

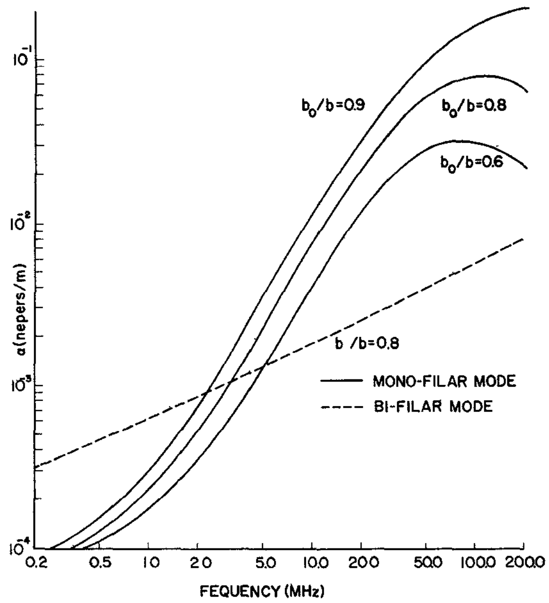

Fig. 3. Attenuation constant of the monofilar and the bifilar modes of configuration A versus frequency for various values of b_0/b. Wire radii $\rho = 2$ mm.

NUMERICAL RESULTS

Equations (5) and (6) are solved numerically for the two configurations A and B in the frequency range 200 kHz–200 MHz. The resulting values of the attenuation $\alpha_{\text{monofilar}}$ and α_{bifolar} are plotted in Figs. 2–4. The following physical constants are assumed in Fig. 2: $2a = 4$ m, $2b = 3$ m, $x_0 = a/2$, $d = a/100$, $\rho = 1$ mm, σ_w (the conductivity of the wires) $= 10^6$ mho/m, $\epsilon_e = 10\epsilon_0$, and $\sigma_e = 10^{-2}$ mho/m.

In contrast with the monofilar mode, the attenuation of the bifilar mode is almost insensitive to variations of the parameter b_0/b in all the frequency ranges considered and hence α_{bifilar} is shown for only one value of this parameter. To show the effect of varying the intrinsic parameters of the TL, the wire radii are increased to 2 mm in Fig. 3. By comparing with Fig. 2, it is seen that α_{bifilar} is appreciably reduced at all frequencies, while $\alpha_{\text{monofilar}}$ is hardly affected for frequencies above about 12.5 MHz and considerably reduced at lower frequencies. It is interesting to note the higher values of attenuation displayed by the bifilar mode over the monofilar mode for frequencies below a certain value in both Figs. 2 and 3.

The preceding observations can be explained as follows: as the frequency is reduced below about 100 MHz, the guide walls behave more as good electrical conductors, hence reducing the attenuation of the monofilar mode. Thus, at low frequencies (of the order of a few megahertz and less), the attenuation of both modes becomes solely dependent on the TL intrinsic parameters σ_w and ρ. Furthermore, the ohmic losses of the TL are normally higher for the bifilar mode than those for the monofilar mode and hence the higher attenuation of the former mode.

The attenuation curves for configuration B are shown in Fig. 4

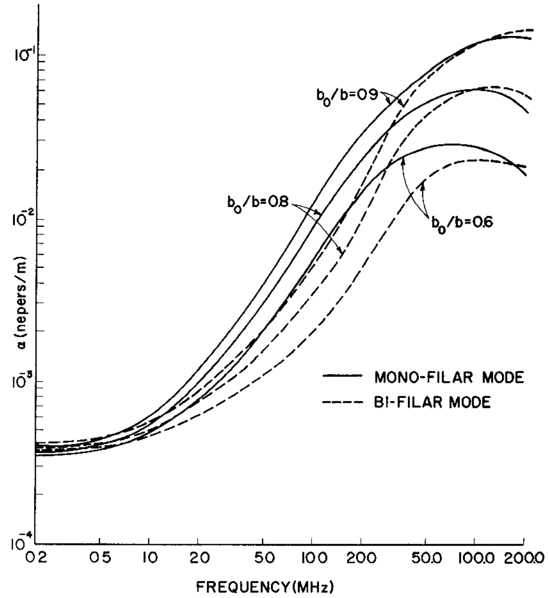

Fig. 4. Attenuation constant of the monofilar and the bifilar modes of configuration *B* versus frequency for various values of b_0/b. Wire radii = 1 mm.

for the same physical constants of Fig. 2. In this case, the bifilar mode shows strong dependence on the parameter b_0/b, supposedly because its fields are spread over the guide cross section and are significantly affected by the tunnel walls. As a further consequence of that, α_{bifilar} is much more frequency dependent than it is for configuration *A*.

It is relevant to mention here that similar results to those presented here are obtained for a circular guide with lossy dielectric walls by Wait and Hill (private communication). We find a complete consistency between the mode characteristics in both guide geometries. This provides some confidence in the adequacy of the model used here for the rectangular tunnel.

A final remark on the preceding model is now due. All the results of Figs. 2–4 are obtained for a waveguide model with side walls that are perfect electric conductors. An alternative model is one in which these walls are perfect magnetic conductors [6]. We computed values of attenuation rates for this model and it was found that the monofilar modes (and the bifilar mode of configuration *B*) show much higher attenuation rates for frequencies below 25 MHz, while near 200 MHz the attenuation rates are only slightly different from those obtained for the first model. We believe, however, that the model with perfect electric side walls is a better approximation to the actual tunnel in the frequency range considered here, since the tunnel walls do tend to behave as good electrical conductors as the frequency is lowered.

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