Finite and Infinite Lossy Conductors over a Lossy Ground Plane Excited by an Electromagnetic Pulse

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***Abstract*—We report a frequency-domain method based on transmission line theory that we name ATLOG – Analytic Transmission Line Over Ground – to model finite or infinite wires interacting with a conducting ground excited by an electromagnetic pulse. This method allows for the treatment of finite or infinite lossy, coated wires above a lossy ground, as well as resting on or buried beneath the ground. Comparisons with full-wave simulations strengthen the validity of the proposed method.**

Keywords*—*transmission line theory; long-wire coupling; EMP excitation; finite/infinite wires over conducting grounds; lossy wires

I. Introduction

We provide results for the current induced by an electromagnetic pulse (EMP) on finite or infinite conductors interacting with a conducting ground. Carson [1] reported the original treatment of a wire above a conducting ground, and found the formula for the ground impedance at low frequencies. Many contributions to this problem were provided by Sunde [2], including approximations for the ground admittance and approximations for buried insulated conductors. The exact solution of a filament above a conductive ground was given by Wait [3, 4]. We direct the reader to the introduction of [5] for a more in-depth discussion of previous works.

We report here a frequency-domain transmission line model of finite or infinite insulated wires, referred to as ATLOG – Analytic Transmission Line Over Ground [5]. We aim to obtain simple results for the current induced by the EMP radiation when the wire is either above, below, or resting on the ground. When compared to the generally slow calculation time of full-wave simulators, a benefit of the proposed ATLOG method is that it provides fast and reliable results. The time response of the induced current is obtained using an inverse Fourier transform of the current in the frequency domain. We consider the presence of losses for both the wire and the ground plane, usually not treated in previous works; some considerations toward this problem were treated before (see [5]), but not for the general cases we analyze here. The complete transmission line approximation [6], which yields explicit expressions for the transmission line parameters, forms the basis for the approach presented here. Reference works on EMP coupling to long lines along with many additional references can be found in [7-9].

II. ATLOG Model for a Conducting Wire over a Ground Plane under EMP Plane Wave Excitation

Consider the schematic depicted in Fig. 1, where the incident plane wave is polarized in the plane containing the wire and the ground with incidence angle θ_0 with respect to the z axis. The transmission line parameters for the cases above, below, or resting on the ground are reported in [5, 10]. The Bell Labs EMP waveform [5, 11], as well as a sine-squared waveform [5] are used for excitation.

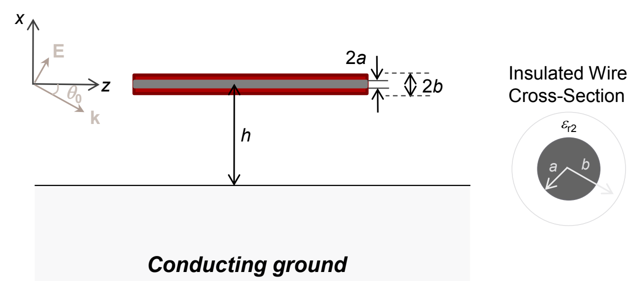

Fig. 1. Schematic of the problem: an EMP plane wave illumination excites a finite or an infinite (coated) conducting wire located at a distance h from a conducting ground plane.

A. Infinite lines

Following [5, 10], the general solution of the transmission-line equation

$$\left(\frac{d^2}{dz^2}+k_L^2\right)I=-YA_n e^{-jzk_0\cos\theta_0}, \quad (1)$$

with $k_L=\sqrt{-ZY}$, k_0 the free space wavenumber, and A_n a coefficient taking into account the location of the wire with respect to the ground (i.e. h greater than or equal to wire coating radius or smaller than minus wire coating radius), is found as

$$I=-\frac{YA_n e^{-jzk_0\cos\theta_0}}{k_L^2-k_0^2\cos^2\theta_0}. \quad (2)$$

B. *Finite lines*

Following [5], the solution of the transmission-line equation

$$\left(\frac{d^2}{dz^2}-\gamma_L^2\right)I=-YE_z^{\mathrm{inc}} \tag{3}$$

with $\gamma_L^2=ZY$, is given by [7, 12]

$$\begin{aligned} I(z)&=[K_1+P(z)]e^{-\gamma_L z}+[K_2+Q(z)]e^{\gamma_L z} \\ V(z)&=\sqrt{\frac{Z}{Y}}\left\{[K_1+P(z)]e^{-\gamma_L z}-[K_2+Q(z)]e^{\gamma_L z}\right\}, \end{aligned} \tag{4}$$

with $P(z)$, $Q(z)$, K_1, and K_2 defined as in [5].

III. Comparison with Full-Wave Simulations

We employ the EMPHASIS [13] and CST Microwave Studio full-wave codes to compare to ATLOG results in Fig. 2 for various wire radii. One can see a good agreement among the three methods (particularly for the smaller wire radii [5, 13]), confirming the estimated induced current.

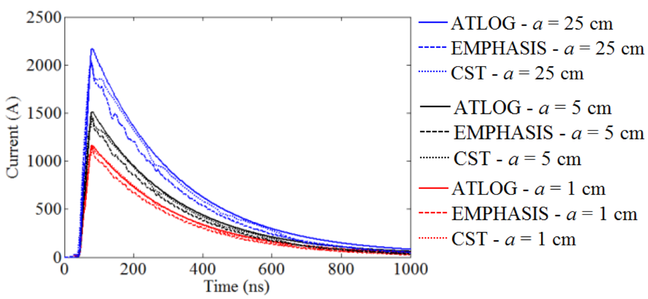

Fig. 2. Current versus time for the case of normal incidence assuming a PEC wire (no coating) with $a=25\,\mathrm{cm}$, $a=5\,\mathrm{cm}$, and $a=1\,\mathrm{cm}$ on top of a PEC ground for a Bell Labs EMP waveform. The current is computed at $z = 0$.

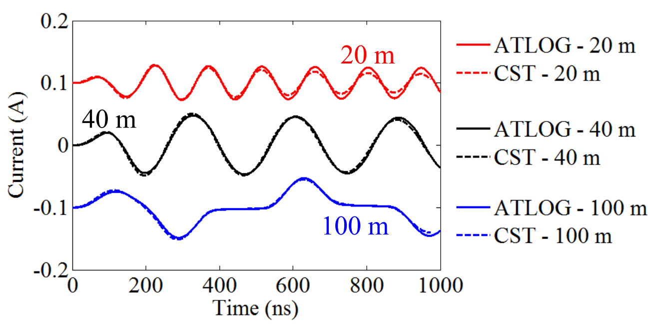

Fig. 3. Current versus time for the case of normal incidence assuming a 20-, 40-, and 100-m-long finite wire with $a=1\,\mathrm{cm}$ (no coating) for a sine-squared waveform with 200 ns pulse and accounting for a wire conductivity of $\sigma_0=5.96\times10^7$ S/m , a lossy ground with $\sigma_4=0.1\,\mathrm{S/m}$ and $\varepsilon_4=20\varepsilon_0$, and $h=5\,\mathrm{m}$. The current is computed at the center of the finite line. The 20 m result is shifted by +0.1, and the 100 m result is shifted by –0.1.

We then use CST Microwave Studio to validate the ATLOG result for finite wires. We consider open-circuited finite wires with length of 20 m, 40 m, and 100 m and report the result in Fig. 3 (the ATLOG result accounts for a capacitive load $C=6.35\,\mathrm{pF}$ arising from the fringing fields accounted for in full-wave simulation at the open-circuited wire terminations). We see good agreement between CST and ATLOG for all the line lengths analyzed. Evidence of possible radiation damping is present in the full-wave simulation of the 20 m case. This effect is even greater for shorter lines and it could be accounted for by the addition of a lumped load determined from examination of the radiated power.

IV. Conclusion

A frequency-domain transmission-line model, named ATLOG, was formulated here for the electromagnetic pulse response of finite or infinite wires interacting with a conducting ground. It allows for the treatment of finite or infinite lossy, coated wires above, resting on, and buried beneath lossy grounds. We compared ATLOG results to EMPHASIS and CST Microwave Studio full-wave results for both infinite and finite wires, validating our proposed model.

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References

[1] J. R. Carson, "Wave propagation in overhead wires with ground return," *Bell Syst. Tech. J.,* vol. 5, pp. 539-554, 1926.

[2] E. D. Sunde, *Earth Conduction Effects in Transmission Systems*. New York: Dover, 1967.

[3] J. R. Wait, "Theory of wave propagation along a thin wire parallel to an interface," *Radio Sci.,* vol. 7, pp. 675-679, 1972.

[4] J. R. Wait, "Tutorial note on the general transmission line theory for a thin wire above the ground," *IEEE Trans. Electromagn. Compat.,* vol. 33, pp. 65-67, 1991.

[5] S. Campione, L. K. Warne, L. I. Basilio, C. D. Turner, K. L. Cartwright, and K. C. Chen, "Electromagnetic pulse excitation of finite- and infinitely-long lossy conductors over a lossy ground plane," *J. Electromagnet. Wave. Appl.,* DOI: 10.1080/09205071.2016.1270776, 2017.

[6] K. C. Chen and L. K. Warne, "A uniformly valid loaded antenna theory," *IEEE Trans. Antennas Propag.,* vol. 40, pp. 1313-1323, 1992.

[7] E. F. Vance, *Coupling to Shielded Cables*. New York: John Wiley and Sons, 1987.

[8] K. S. H. Lee, *EMP Interaction: Principles, Techniques, and Reference Data*. Washington: Hemisphere Publishing Corp., 1986.

[9] F. M. Tesche, M. V. Ianoz, and T. Karlsson, *EMC Analysis Methods and Computational Models*. New York: John Wiley & Sons, Inc., 1997.

[10] L. K. Warne and K. C. Chen, "Long line coupling models," *Sandia National Laboratories Report,* SAND2004-0872, Albuquerque, NM, 2004.

[11] R. Sherman, *EMP Engineering and Design Principles*. Whippany: Bell Telephone Laboratories, Technical Publication Dept., 1975.

[12] S. Campione, L. I. Basilio, L. K. Warne, H. G. Hudson, and W. L. Langston, "Shielding effectiveness of multiple-shield cables with arbitrary terminations via transmission line analysis," *Prog. Electromagn. Res. C,* vol. 65, pp. 93-102, 2016.

[13] C. D. Turner, M. F. Pasik, D. B. Seidel, T. D. Pointon, and K. L. Cartwright, "EMPHASIS/Nevada UTDEM User Guide Version 2.1.1," *Sandia National Laboratories Report,* SAND2014-16735, Albuquerque, NM, 2014.