Effects of Trains on Cutoff Frequency and Field in Rectangular Tunnel as Waveguide

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***Abstract*—Effects of trains in a rectangular tunnel on the cutoff frequency and field were determined at the range of VHF, UHF, and SHF bands by the finite-element method. According to this study, the tunnel is a transmission channel of high-pass type waveguide. The tunnel and the trains were assumed to be infinitely long and fully conductive. Generally speaking, the trains in the tunnel lowered TE_{nm} wave cutoff frequencies and raised TM_{nm} cutoff frequencies. Closer monitoring, however, has shown that the above results may be reversed, depending on the conditions.**

The field is represented by contour lines. Thus, its change is clearly shown by a change in the distribution of the lines caused by the train in the tunnel. Although the train changed field distribution for both TE_{nm} and TM_{nm} mode, greater changes were usually observed in higher order mode fields.

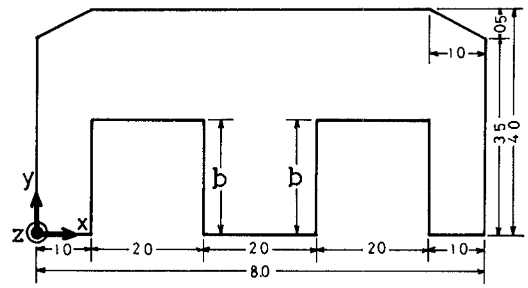

Fig. 1. The boundary of the tunnel which trains entered in two rows (all dimensions in meters).

I. Introduction

SECURE communications are a prerequisite in tunnels, underground markets, and mines, including coal mines. Recently, an international conference on communications in tunnels was held to enhance public safety and prevent disasters [1]. In underground environments, communicability is vital in emergency cases such as fires, as well as in routine management operations. This study aims at establishing a basis for solving such problems.

Everyone has experienced that radio broadcasting cannot be heard in the tunnel. However, when a certain relationship exists between the cross section of the tunnel and the free-space wavelength of the electromagnetic wave, the wave propagates through the tunnel, thus permitting radio communications that utilize the tunnel as a waveguide [2]–[6]. This communication method is useful in emergency cases caused by fire, because it is reliable, has high mobility, and is readily available.

The effects of trains in tunnels on cutoff frequencies are yet to be clarified. In addition, the cross section of an actual tunnel is not of the typical rectangular shape, but of chipped rectangles. Trains in the tunnel complicate its cross section further. This study uses the following assumptions as the first step in determining the characteristics involved in such a complicated problem: the rectangular tunnel is replaced by a model which is a conductor with an infinite length and has the same cross section as that of the tunnel; trains are regarded as a rigid conductor, with a fixed width (2.0 m) and height of b, the length of which is infinite in the direction of radio wave transmission. Thus, this model can be regarded as "uniform cross section." Therefore, the complicated problem is reduced to a two-dimensional one in which cutoff frequencies can be determined by finite-element method. The results have revealed that cutoff frequencies for ordinary tunnels are in the lower region of the VHF band and that trains in the tunnel may change the cutoff frequency, depending on wave modes.

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II. Theory

Fig. 1. shows a model for trains in a tunnel. The tunnel and the trains are both assumed to be straight and infinitely long, and the tunnel wall and the trains are assumed to be perfect conductors. The cross section of the tunnel is taken as the $X-Y$ plane and the direction of radio wave transmission as the Z axis. The internal region of the tunnel is expressed as G and the boundary of G (the walls of the tunnel and the trains) as Γ. With this notation, the TE_{nm} modes and the TM_{nm} modes are expressed by the following Helmholtz equation:

i) TE_{nm} modes

$$\nabla^2 H_z + k^2 H_z = 0, \quad \text{in } G$$
$$\partial H_z / \partial n = 0, \quad \text{on } \Gamma \tag{1}$$

ii) TM_{nm} modes

$$\nabla^2 E_z + k^2 E_z = 0, \quad \text{in } G$$
$$E_z = 0, \quad \text{on } \Gamma \tag{2}$$

where H_z is the Z component of the magnetic field, E_z is the Z component of the electric field, k is the cutoff wave number, and $\partial/\partial n$ is the partial differentiation along a normal line against the boundary Γ.

The functional $I[\phi]$ corresponding to the above Helmholtz equation is expressed as follows:

$$I[\phi] = \iint_G \left\{ \left(\frac{\partial \phi}{\partial x} \right)^2 + \left(\frac{\partial \phi}{\partial y} \right)^2 \right\} dx\,dy - k^2 \iint_G \phi^2\,dx\,dy \tag{3}$$

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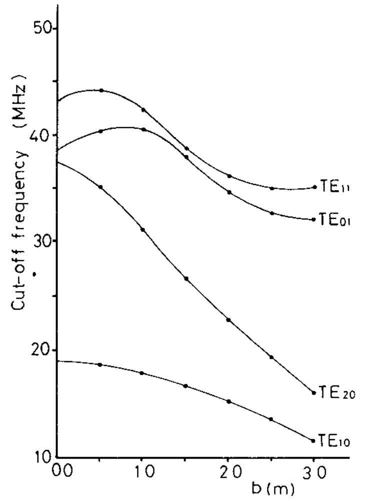

Fig. 2. Cutoff frequency of the TE_{nm} mode.

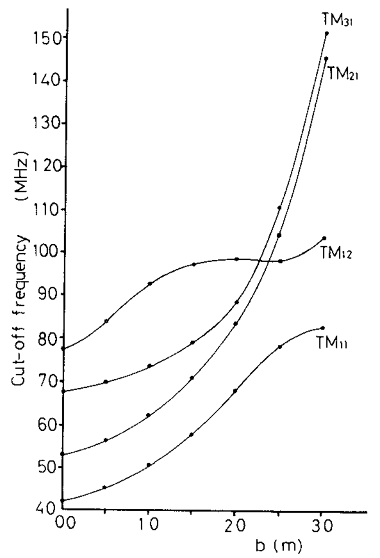

Fig. 3. Cutoff frequency of the TM_{nm} mode.

where $\phi = H_z$ (or E_z).

This function is solved for each set of boundary conditions by applying the finite-element method [7].

The elements used are triangular ones on which ϕ is approximated as a quadratic function.

If each eigenvalue $(k)^2$ is determined, the cutoff frequency f_c is obtained from the following formula:

$$f_c = k/2\pi\sqrt{\epsilon_0\mu_0}.$$

$\phi(H_z$ or $E_z)$ is determined as an eigenvector of each eigenvalue.

III. Numerical Analysis

In this paper, the inside of the tunnel is divided into over 130 elements. Therefore, the relative errors for up to the TE_{20} mode and for up to the TE_{31} mode are less than 0.05 percent and 0.3 percent, respectively.

Figs. 2 and 3 show cutoff frequency change by train height b for TE_{10} modes and for TM_{11} modes. Figs. 4 and 5 give the ϕ distribution of the individual modes when train height b is altered to a) 1.0 m, b) 2.0 m, and c) 3.0 m.

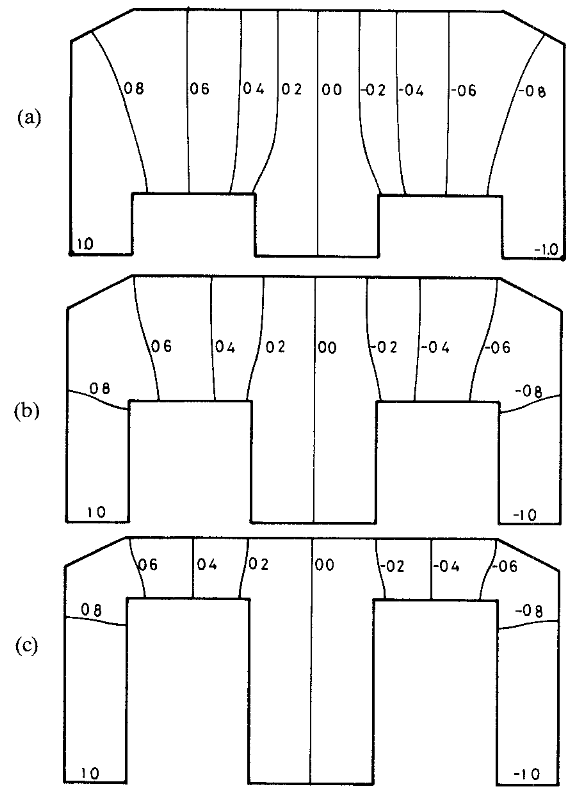

Fig. 4. The field pattern of the TE_{10} mode.

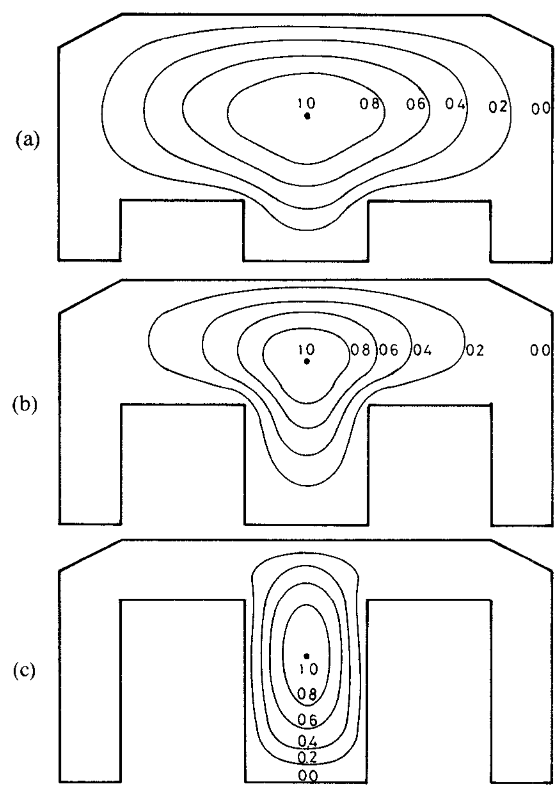

Fig. 5. The field pattern of the TM_{11} mode.

In these figures, the maximum value of ϕ is specified as 1, and ϕ represents H_z for the TE_{10} modes and E_z for the TM_{11} modes. The field distribution in the tunnel depends on the train height b, as shown in Figs. 4 and 5.

The cutoff frequency of the waveguide f_{nm} increases with decreasing the dimensions of the cross section of tunnels ($f_{nm} = \sqrt{(n/A)^2 + (m/B)^2}/(2\sqrt{\mu\epsilon})$ where A is the width of the waveguide, B is the height of the waveguide, μ is the permeability of the medium, and ϵ is the permittivity of the medium).

In Fig. 5, the width of field distribution decreases with increasing the train height b, thus the effective width of the tunnel decreases with increasing train height b, therefore in case of TM-modes the cutoff frequency become high, as shown in Figs. 3 and 5.

Otherwise, in the case of TE modes, the effective width of the tunnel increases with increasing the train height b, therefore cutoff frequency becomes low, as shown in Figs. 2 and 4.

IV. Conclusion

The cutoff frequency for TE_{nm} modes and TM_{nm} modes was determined by using the finite-element method and a model tunnel in which there are a long trains. As a general rule, the trains in the tunnel lower the cutoff frequency for the TE_{nm} modes and raise that for the TM_{nm} modes.

Close monitoring, however, has revealed that the cutoff frequencies for the TE_{01} and TE_{11} modes may be raised, depending on the value b and that the cutoff frequencies for the TM_{12} mode may be lowered, depending on its value.

This study analyzed the effects of trains in tunnels on the basis of certain assumptions and elucidated part of the basic characteristics. It achieved the anticipated results because practical modes are limited to the lower order ones among numerous transmissible modes. The problem of transmission loss shift due to trains will be studied in a future paper.

Acknowledgment

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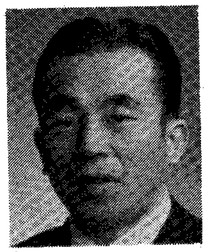

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