Numerical estimation for TEM horn antennas with transmission line taper shapes

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Abstract: The design of transverse electromagnetic (TEM) horn antennas has to consider impedance matching between the feeding point and the aperture. To achieve good impedance matching, several typical tapered transmission lines are applied to the taper shape of TEM horns in this study. The numerical estimation of the antenna characteristic of each TEM horn is performed using the finite integration method. An exponential taper is most applicable to the antenna shape among those transmission line tapers. An exponentially tapered TEM horn, however, has problems in maintaining a single main lobe in the radiation pattern. We propose a shortened exponentially tapered TEM horn in which has a simple structure that improves the radiation directivity, and the estimation results show its effectiveness as a broadband antenna.

Keywords: TEM horn antenna, transmission line taper, impedance matching, finite integration method, exponentially tapered TEM horn, shortened exponentially tapered TEM horn

Classification: Electromagnetic Compatibility (EMC)

References

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1 Introduction

TEM horn antennas are widely used for UWB (ultra-wideband) systems such as radar and wireless communication and for electromagnetic compatibility (EMC) estimation due to their low pulse distortion. Recently, this antenna type has been explicitly specified in an international EMC standard [1] as a field generating antenna used for radiated immunity testing in close proximity. A basic TEM horn consists of linearly tapered plates. For impedance matching of the feeding point and the aperture, a linearly tapered TEM horn with continuous resistive loading has been proposed [2, 3]. A TEM horn with an exponentially tapered shape has also been designed, and which has the advantage of obtaining smooth impedance variations without resistive loading [4]. This result suggests the possibility of applying other well-known tapered transmission lines, such as the Klopfenstein taper, to the antenna shape. However, the effectiveness of these transmission lines as broadband antennas has not been sufficiently confirmed. Although the TEM horn with an exponentially tapered is useful for a broadband antenna, it does not maintain a single main lobe in the radiation pattern over some part of its frequency range. An exponentially tapered TEM horn with arc curvature was subsequently proposed to remove the fluctuations of the main lobe [5].

In this paper, we discuss the antenna characteristics of TEM horns with antenna shapes based on typical tapered transmission lines, including exponential, triangular [6], Klopfenstein [7], and Hecken [8] tapers, and verify whether they are effective as broadband antennas. In this numerical estimation using the finite integration method (FIM), the TEM horns were designed for EMC measurements from 400 MHz to 6 GHz. From the results of numerical analysis for the TEM horns, we propose a shortened exponentially tapered TEM horn, in which has a very simple structure, optimized to maintain a single main lobe.

2 TEM horn

A TEM horn antenna consists of two tapered metal plates fed by a coaxial line. To obtain good reflection characteristics, the antenna structure has to be designed considering impedance matching of the feeding point and the aperture of the antenna. For a TEM horn with a linearly tapered shape, a resistively loaded taper is used to reduce reflections [2, 3]. To achieve good impedance matching without resistive loading, typical tapered transmission lines are applied to the antenna shape, i.e., the separation of two plates. The taper shapes we compared are exponential [6], triangular [6], Klopfenstein [7], and Hecken [8] types. The variations of the characteristic impedance $Z(z)(0 \leq z \leq L)$ for each taper of length $L$, source impedance $Z_0$, and load impedance $Z_L$ are expressed as follows:
exponential taper [6]:

\[ Z(z) = Z_0 e^{z/L \ln(Z_L/Z_0)} , \]  

triangular taper [6]:

\[ Z(z) = \begin{cases} 
Z_0 e^{2z(L/2) \ln(Z_L/Z_0)} & (0 \leq z \leq L/2), \\
Z_0 e^{(z^2/2 + z/2 - z^2 - 1) \ln(Z_L/Z_0)} & (L/2 \leq z \leq L),
\end{cases} \]  

Klopfenstein taper [7]:

\[ \ln Z(z) = \frac{1}{2} \ln(Z_0Z_L) + \frac{\Gamma_0}{\cosh A} A^2 \phi \left( \frac{2z}{L} - 1, A \right) , \]  

where

\[ \phi(x, A) = \int_0^x \frac{I_1(A \sqrt{1 - y^2})}{A \sqrt{1 - y^2}} dy, \quad \Gamma_0 = \frac{Z_L - Z_0}{Z_L + Z_0} , \]  

where \( I_1 \) is the first kind of modified Bessel function and \( A \) is a parameter for the tapered line curve, and

Hecken taper [8]:

\[ \ln Z(z) = \frac{1}{2} \ln(Z_0Z_L) + \frac{1}{2} \ln \left( \frac{Z_L}{Z_0} \right) \frac{B}{\sinh B} \varphi \left( B, \frac{2z}{L} - 1 \right) , \]  

where

\[ \varphi(B, x) = \int_0^x I_0(B \sqrt{1 - y^2}) dy, \]  

where \( I_0 \) is the modified zero-order Bessel function and \( B \) is a parameter for the tapered line curve.

Fig. 1. Analytical model for TEM horn with transmission line taper shape.
In this numerical estimation, the TEM horn was designed for EMC measurements in the frequency range from 400 MHz to 6 GHz. The antenna length \( L \) and the aperture dimension are set to half the wavelength of the lowest frequency. The other antenna parameters are the input impedance at the coaxial feeding point of 50 \( \Omega \) \( (= Z(0)) \) and the characteristic impedance at the square aperture of 377 \( \Omega \) \( (= Z(L)) \). The variations of the characteristic impedance for each taper shape is indicated in Fig. 1(a). Assuming that the TEM horn consists of minute parallel plates, as shown in Fig. 1(b), the width \( w(z) \) at the location \( z \) of a taper plate can be approximated as follows from the plate separation \( h(z) \) and characteristic impedance \( Z(z) \) [4]:

\[
w(z) = \frac{h(z)}{Z(z)} 120\pi. \tag{5}
\]

Each antenna model is composed of the taper structure determined using Eqs. (1)–(5), as shown in Fig. 1(c). The antenna characteristics for TEM horns with transmission line tapers were estimated numerically using a full-wave electromagnetic solver (CST MW-Studio [9]) based on FIM. The TEM horn has a balanced structure with parallel plates and is fed by an unbalanced coaxial cable. Therefore, a broadband balun is generally needed to feed the antenna. In this simulation, TEM horns are directly fed without a coaxial cable.

Fig. 2(a) and (b) show the calculation results of the reflection \( |S_{11}| \) and the gain characteristics of the TEM horns, respectively. Each antenna exhibits a satisfactory reflection characteristic over the broadband frequency range owing to the effects of impedance matching by the tapered transmission lines. By applying

![Fig. 2. (a) Reflection and (b) gain characteristics of TEM horns with typical transmission line tapers. (c) Gain and (d) radiation pattern (2.5 GHz) of exponentially tapered TEM horn.](image)
transmission line tapers to the antenna shape, impedance matching without resistive loading is possible. However, as shown in Fig. 2(b), the antennas applying the triangular and Klopfenstein tapers have many large ripples in the gain profile. On the other hand, the antenna with the exponential taper has flat gain characteristics, allowing it to be used as a broadband antenna. When the constant $B$ is small for the Hecken taper (e.g., $B = 0.1$), the shape is in agreement with that of the exponential taper. When the Hecken taper has a slightly different shape from the exponential taper (e.g., when $B = 2$), the gain characteristic deteriorates at higher frequencies. The exponential taper is therefore the most suitable as the taper structure of a TEM horn among the investigated tapered transmission lines. However, the maximum gain of the antenna is not located in front of the antenna at over some part of its frequency range, as shown in Figs. 2(c) and (d).

3 Improved TEM horn

For antennas used for EMC measurements, the direction of maximum radiation is commonly designed to be in front of the antenna. We propose an improved TEM horn that resolves the directivity problem of the exponentially tapered TEM horn. As a similar approach to improve the directivity, a TEM horn with arc curvature shape has been proposed [5]. The antenna shape that we designed has a very simple structure compared with the arc curvature shape. The modified exponential taper is shortened by removing approximately 10% of the antenna length from the aperture, as shown in Fig. 3(a). The cut length ($dl$) was determined by optimization of the directivity by numerical simulation. That is, the difference between the on-axis gain and the maximum gain was calculated for each cut length, as shown in Fig. 3(b).

![Fig. 3. Shortened exponentially tapered TEM horn.](image-url)
When the cut length was 6%, i.e., $0.06 \times L(=dl)$, or more, the on-axis gain matched the maximum gain. The gain characteristic and radiation pattern of the exponentially tapered TEM horn with a cut length of 10% are respectively shown in Figs. 3(c) and (d). The direction of maximum gain is directly in front of the antenna for a given frequency range, and also the radiation pattern maintains a single main lobe. Although the gain is decreased at lower frequencies resulting from the reduced antenna length, a relatively flat characteristic is obtained. A cut length of 6% to 12% is suitable considering the effect of gain reduction at lower frequencies. This upper limit of the cut length (12%) was determined so that the gain reduction did not exceed 3 dB.

4 Conclusion

In this study, we evaluated TEM horn antennas with a taper shape applied several typical transmission line tapers, including exponential, triangular, Klopfenstein, and Hecken types. Numerical analyses of TEM horns designed for EMC measurements from 400 MHz to 6 GHz were performed using FIM. Each TEM horn exhibited a satisfactory reflection characteristic owing to the effect of impedance matching by the transmission line. However, only a TEM horn with an exponentially tapered shape had a gain characteristic that enables its use as an antenna. The single main lobe of the exponential-type horn, meanwhile, is not maintained at some part of frequency range. We proposed a shortened exponentially tapered TEM horn that resolves this directivity problem, and the results obtained show its effectiveness for use as, for example, an EMC broadband antenna. The remaining problem is to design an adequate broadband balun for an unbalanced TEM horn and then to confirm the numerical results experimentally.