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RESEARCH ARTICLE

Microwave Doppler velocity measurement using tapered rectangular waveguide antenna with pattern offset correction

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Abstract

Rectangular waveguide antenna has been often used in velocity measurement based on microwave Doppler principle for its advantages of high directivity, high radiation efficiency, and reliability. In addition to a waveguide antenna with a straight aperture, a tapered waveguide antenna is frequently required in measuring flow velocities in a pipe. In the common sense, the maximum radiation direction is usually taken to be along the axial direction of the waveguide. This is well understood for a conventional straight open-ended waveguide antenna with an aperture perpendicular the axis of the waveguide. However, for a tapered rectangular waveguide antenna with an aperture at an angle to the axis of the waveguide, there exists an offset from the axial direction for the maximum radiation direction. In this paper, a tapered rectangular waveguide antenna with a tapering angle α is analyzed and studied experimentally. For α =45°, the results show that the maximum radiation has an offset of 25.5° in theory, 25° in simulation and 30° in measurement from the axial direction of the waveguide. The experimental study also shows that when this radiation pattern offset is taken into account, the velocities measured using the microwave Doppler principle agree well with the theoretically calculated free-fall velocity.

KEYWORDS
microwave Doppler, offset, rectangular waveguide antenna, tapered

1 | INTRODUCTION

Antenna is an important device in wireless communication and radar systems.[1,2] With the advantages of compact structure, high directivity, high radiation efficiency, and reliability,[3–5] rectangular waveguide antenna is often used as a front-end in industrial measurement such as the velocity measurement of moving gas-solid flows in pipes.[6,7]

Rectangular waveguide is a regular wave guiding device made from metal material (copper, aluminum, etc.) with a rectangular cross section,[8] and its internally filled medium is usually air, as shown in Figure 1. A rectangular waveguide antenna is formed when the rectangular waveguide has an open end. At the open end, radiation emerges due to the mutual conversion between changing electric field and changing magnetic field. The fields around antenna can be divided into near field region (Fresnel region) and the far field region (Fraunhofer region). Energy swings back and forth in the near field region and radiates outward. The main working area of antenna is in the far field region.[9]

Waveguide antenna usually has a straight open end. On the other hand, in many applications, such as flow velocity measurement in a pipe, a tapered waveguide antenna is required.[10–12] However, there is little research on the radiation of tapered waveguide antenna. As the radiation characteristics have a direct effect on the determination of velocity measured using the microwave Doppler principle. We therefore carry a study on this subject by theoretical analysis, simulation, and practical measurement and report in this paper the outcome of the study. In addition, the results are applied to the velocity measurement of solids flowing in a pipe. The accuracy of the velocity measurement is assessed by comparing with the theoretical free-fall velocity of the solid. Further details are given in the following sections.

This paper is organized as follows. In Section 2, the modeling of tapered rectangular waveguide antenna is presented and the characteristics of tapered waveguide antenna

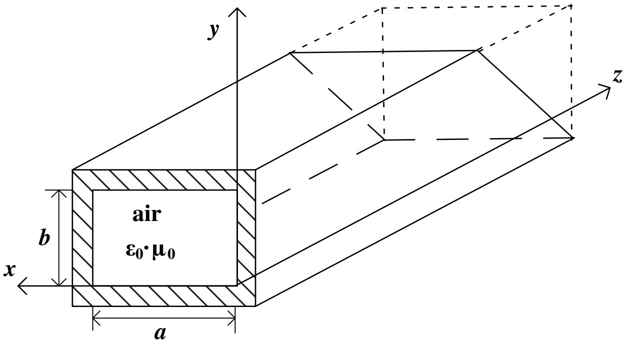

FIGURE 1 Rectangular waveguide

are analyzed. Pattern offset corrections are identified. In Section 3, the results obtained by simulation and measurement are compared with theoretical results. In Section 4, microwave Doppler velocity measurement principle is described, and velocity measurement using the tapered waveguide antenna with pattern offset corrections is presented. Finally, conclusions are given in Section 5.

2 | THEORETICAL ASPECT

The rectangular waveguide antenna is shown in Figure 1. The long side is in x-axis with a length of $a = 1.6$ cm, and the short side is in y-axis with a length of $b = 1.0$ cm while the variation in z-axis is tapered. The rectangular waveguide antenna is installed on the measuring pipe with an angle of α between the waveguide axis and the normal direction of the cross section, as shown in Figure 2.

The operating frequency is considered to be 10.525 GHz and the corresponding wavelength is $\lambda = c/f = 2.85$ cm with c being the speed of light in free space. The working frequency for the TE$_{10}$ mode of this waveguide antenna is 9.38 GHz, which is smaller than the working frequency of 10.525 GHz, while the cut-off frequencies of other modes are beyond the working frequency.[13,14] Hence, the TE$_{10}$ mode is the only mode that can be transmitted in this rectangular waveguide. Based on the Maxwell's equations, for the lowest TE$_{10}$ mode, the electric field component is in y-axis, and the magnetic field components are in z-axis and x-axis. They can be expressed as follows.[15–17]

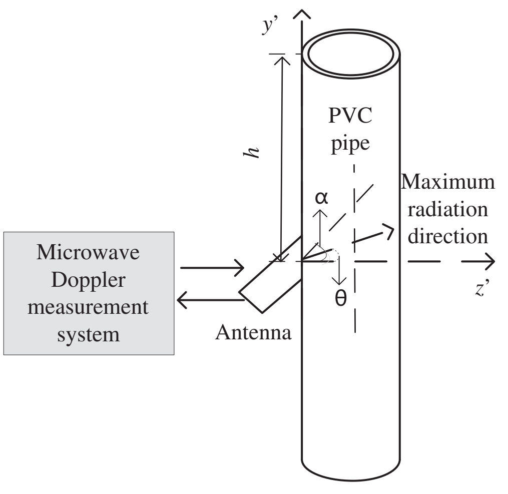

FIGURE 2 Diagram of antenna mounting on a pipe

TABLE 1 Change of θ with α

α/(°)	0	10	20	30	40	45
θ/(°)	0	4.7	9.3	13.5	17.4	19.5

$$E_y = \frac{-j\omega\mu_0 a}{\pi} H_0 \sin\frac{\pi x}{a} e^{-j\beta z} \tag{1}$$

$$H_x = \frac{j\beta a}{\pi} H_0 \sin\frac{\pi x}{a} e^{-j\beta z} \tag{2}$$

$$H_z = H_0 \cos\frac{\pi x}{\mathrm{a}} e^{-j\beta z} \tag{3}$$

$$H_y = E_x = E_z = 0 \tag{4}$$

where H_0 is the amplitude of the magnetic field in the z direction, which is determined by the intensity of the excitation source, β is the phase constant of the TE$_{10}$ mode, ω is the angular frequency, $\varepsilon = \varepsilon_0$ is the dielectric constant of air and $\mu = \mu_0$ is the permeability of air.

Based on the fields above, the electric fields at the aperture of the tapered rectangular waveguide with the coordinates shown in Figure 2 can be expressed as:

$$E_{y'} = \frac{-j\omega\mu_0 a}{\pi} \cos\alpha H_0 \sin\frac{\pi x}{a} e^{-j\beta y' \sin\alpha} \tag{5}$$

$$E_{z'} = \frac{j\omega\mu a}{\pi} \sin\alpha H_0 \sin\frac{\pi x}{a} e^{-j\beta y' \sin\alpha} \tag{6}$$

As $E_{z'}$ is normal to the aperture surface, it does not contribute to the radiation. $E_{y'}$ is tangential to the aperture surface and is the only electrical field component contributing to radiation as an equivalent magnetic surface current. The electric vector **F***(r)* on *YoZ* plane can be derived based on the equivalent magnetic current principle.[18]

$$\mathbf{F}(r) = -\frac{\varepsilon_0 e^{-jkr}}{2\pi r} \vec{e}_z \times \iint E_{y'}\left(x', y'\right) e^{jk \sin\theta y'} \tag{7}$$

The radiated electric field $\mathbf{E}_\theta$ on *YoZ* plane can be obtained as:

$$\mathbf{E}(\theta, f) = -\frac{1}{\varepsilon_0} \nabla \times \vec{F}(r) \tag{8}$$

$$\mathbf{E}_\theta\left(\theta, \varphi = \frac{\pi}{2}\right) = \frac{2abkE_0}{\pi} S_a\left[\frac{kb}{2\cos\alpha}\left(\sin\theta - \frac{\lambda}{\lambda_g}\sin\alpha\right)\right] \tag{9}$$

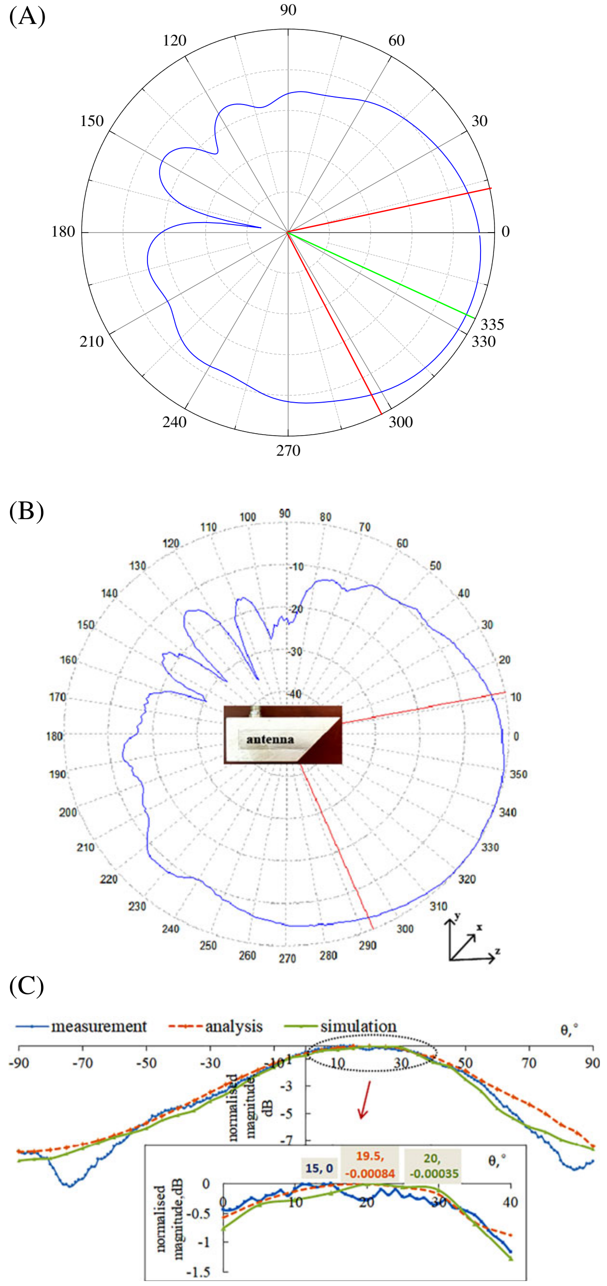

FIGURE 3 (A) Simulated *yOz* plane antenna pattern in dB scale, (B) measured *yOz* plane antenna pattern in dB scale, (C) simulated, measured and analyzed pattern variaiton around the maximum direction (dB) [Color figure can be viewed at wileyonlinelibrary.com]

where $k=\omega\sqrt{\varepsilon_0\mu_0}$ is the wave number in free space, λ is the wavelength in free space, λ_g is the waveguide wavelength given by

$$\lambda_g=\frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}} \tag{10}$$

θ is the angle between maximum radiation direction and z'-axis, and S_a is the sampling function defined as $S_a\ (Q)$ = sin(Q)/Q.

When $\sin\theta=\frac{\lambda}{\lambda_g}\sin\alpha$, i.e.,

$$\theta_m=\arcsin\left(\frac{\lambda}{\lambda_g}\right)\sin\alpha \tag{11}$$

there exists the maximum radiation, and at $\theta=\theta_m$, $E_\theta\max=\frac{2abkE_0}{\pi}$.

For different values of α, their corresponding values of θ are given in Table I. As it can be seen, the offset from the axial direction tends to be larger as α increases. At α $=45^0$, θ = 19.5^0.

3 | SIMULATION, MEASUREMENT, AND ANALYSIS OF THE TAPERED RECTANGULAR ANTENNA

The tapered rectangular waveguide antenna used for measurement study is shown in Figure 3 (b). There is a tapered opening along the short side with an angle of 45°, which is convenient for mounting on a pipe for noninvasive Doppler velocity measurement.

The angle between the waveguide axis and the normal direction of the cross section is α =45°. Based on the calculation in Section 2, the angle between maximum radiation direction and z'-axis is θ = 19.5°. The waveguide wavelength is λ_g = 6.03 cm. The offset angle γ can be calculated as γ = α- θ = 25.5°.

Antenna simulation software CST Microwave Studio is used to simulate the tapered rectangular waveguide antenna, the simulated *yOz* plane antenna pattern in dB scale can be seen in Figure 3(A). The 3 dB beam width[19] of the tapered rectangular waveguide antenna is simulated to be 76° and the maximum radiation is at the angle of θ = 20° or γ = 25°.

In the measurement study, a microwave antenna measurement system is used to measure this antenna. The antenna pattern obtained is shown in Figure 3(B). The 3 dB beam width of the tapered rectangular waveguide antenna is measured to be 78°. The maximum radiation is at the angle of θ =15° or γ= 30°.

More detailed variation around the maximum radiation direction is shown in Figure 3(C). The calculated, simulated and measured the 3 dB beam width and the maximum radiation θ andγ can be compared in Table 2. Comparing to the theoretical value of θ =19.5° or γ = 25.5°, there is a difference of 4.5° for the measurement results and 0.5° for the measurement results in the maximum radiation direction.

TABLE 2 The 3 dB beam width and the maximum radiation angle

	3 dB beam width	θ	γ
Calculated value	86°	19.5°	25.5°
Simulated value	76°	20°	25°
Measurement value	78°	15°	30°

4 | VELOCITY MEASUREMENT WITH THE TAPERED RECTANGULAR ANTENNA AND ERROR ANALYSIS

Based on the analysis above, the tapered rectangular antenna is used for noninvasive Doppler velocity measurement. The theory of the Doppler effect is: when microwave energy is reflected from a moving object, a frequency shift is resulted, such a frequency shift is proportional to its velocity, and it is known as Doppler frequency shift.[20,21] Hence, the measurement of Doppler frequency shift will give the velocity information of the moving object.

Referring to Figure 4, when a sinusoidal microwave is radiated from an antenna towards a moving object at an angle $\phi = \pi/2\text{-}\theta$, the Doppler frequency shift f_d of the reflected wave back to the antenna is given by

$$f_d = \frac{2v}{\lambda} \cos\phi \tag{12}$$

where v is the velocity of the moving object, λ is the wavelength of the radiated wave. Hence, when f_d is measured, the moving velocity can be obtained as,

$$v = \frac{f_d \lambda}{2 \sin\theta} \tag{13}$$

To verify the correctness of the analysis of the tapered rectangular antenna in last section, experiments are carried out as follows.

As shown in Figure 2, a 80 cm long polyvinyl chloride (PVC) pipe with an inner diameter of 54 mm and outer diameter of 60 mm is used. Solids are dropped randomly into the PVC pipe and the amplitude of the reflected voltage signal is sampled and processed to determine the velocity. The signal is radiated through the tapered rectangular waveguide antenna toward moving solids, and the reflected signal is produced and captured by the same antenna. The viewing angle between the electrical axis of the antenna and the direction of the velocity of the solids is $\alpha = 45°$, as shown in Figure 4. The antenna is attached to the PVC pipe located at a distance of $h = 50$ cm from the point where the solids are released. The Doppler signal output after a microwave mixer is sampled at 1 kHz and transferred into a computer for processing using the equations above via an NI data acquisition (DAQ) card.

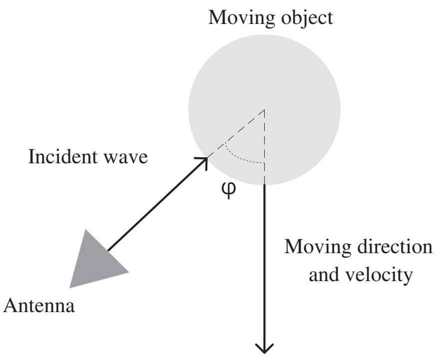

FIGURE 4 Diagram for illustrating Doppler principle

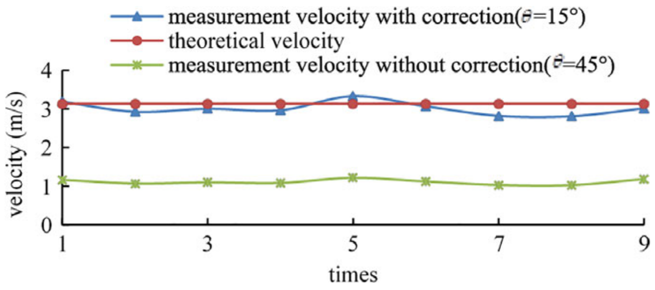

FIGURE 5 Measurement and theoretical velocities of the solids released at a hight of 50 cm [Color figure can be viewed at wileyonlinelibrary.com]

In the experiments, as the solids are dropped in the PVC pipe randomly, their initial directions of motion are unpredictable, velocities measured are different. Therfore, this experiment is repeated for 9 times.

The free-fall velocity of the solids released at the height $h = 50$ cm is 3.13 m/s.

In the common sense, the maximum radiation direction is often taken to be along the axial direction of the waveguide. Then θ in Equation (11) is 45°. The velocity measured ranges from 1.0 m/s to 1.2 m/s, as shown in Figure 5. The average velocity measured is 1.11 m/s (average velocity for 9 times), which deviates significantly from the free-fall velocity (3.13 m/s).

However, from the analysis in the sections above, we know the maximum radiation direction has an offset from the axial direction of the waveguide for 30°, then θ in Equation (11) is 15°. With this pattern offset correction, the velocity of the solids measured ranges from 2.8 m/s to 3.2 m/s and the average velocity is 3.01 m/s, as shown in Figure 5.

The relative errors of the measured velocities from the theoretical value (ie, the free-fall velocity) are within 10% for the case with the pattern offset correction ($\theta = 15°$) and approximately 60% without the correction ($\theta = 45°$) as shown in Figure 6.

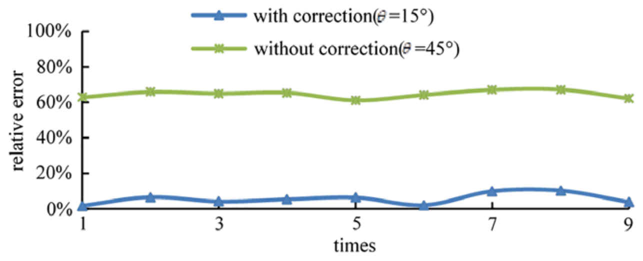

FIGURE 6 Relative errors for velocity measurement with and without pattern offset correction [Color figure can be viewed at wileyonlinelibrary.com]

5 | CONCLUSIONS

In this paper, the radiaiton from a tapered rectangular waveguide antenna is analyzed. A special consideration is made to a tapered rectangular waveguide antenna with a tapering angle of 45°, which is is used for microwave Doppler velocity measurement. Both simulation and experimental studies have been carried out to verify the analytical result. The study shows that the maximum radiation direction deviates from the common sense and has an offset from the axial direction of the waveguide by 25.5° in the analysis and 30° in measurement. The 3 dB beam width of the tapered rectangular waveguide antenna is also measured to be 78°. The measured result agrees fairly well with the simulation and analytical results. The velocities of free-flow solids measured using the microwave Doppler principle agree well with the theoretically calculated free-fall velocity with pattern offset correction and the relative errors are within 10% comparing to 60% approximately without the pattern offset correcton. This thus shows the importance of the pattern offset correcton in applying the microwave Doppler principle for velocity measurement.

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