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Technical Note

Wave propagation in a waveguide with continuous right-angled corners: Numerical simulations and experiment measurements

Wuzhou Yu, Xu Wang, Rui Wu, Jiangling Yu, Zaixiu Jiang *, Dongxing Mao

Institute of Acoustics, Tongji University, No. 1239 Siping Road, Shanghai 200092, China

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This paper studied the acoustic wave propagation in a waveguide with continuous right-angled corners, with emphasis on the effect brought by the distance between the corners. The numerical analyses showed that at middle to high frequencies, the transmission loss (*TL*) of a multi-cornered waveguide was 2–5 dB higher than that of single-cornered and varied with frequency. To explain the performance at peaks and dips in the *TL* curve, analyses on eigenmodes and sound intensity distribution were conducted. The performance of multi-cornered waveguides was experimentally investigated, which fit well with the numerical results. The present study indicates that, for a waveguide with continuous corners, its acoustic performance is not simply a "summation" of two individual single-cornered ones. Both the standing wave modes and the evanescent modes between the corners lead to its complicated frequency performance.

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1. Introduction

Corners are common structures in waveguide systems, which are important factors responsible for generating duct noise in practical use. Miles [1] studied the wave diffraction caused by a right-angled corner by the equivalent circuit method, in which the wave propagation was represented by voltage and current on a transmission line, and the discontinuity in the waveguide was characterized by a scatter matrix. However, the closed algebraic solution to his equations is impossible. Lippert [2] compared his experimental results with a single mode approximation of Miles' theory. Thompson [3] and Bruggeman [4] used a method of matched asymptotic expansion to determine an approximation solution of sound pressure in a waveguide with corner, which provided a good description of the potential flow around the discontinuity. Different form the methods proposed above, Green's function [5] and the Galerkin method [6] have been also adopted, which agreed well with numerical simulation and experiment. Moreover, a waveguide with corners have been studied by numerical approaches for their superior computing efficiency [7–9]. Graf and Pan [9] showed that the numerical method is not mere validation but a tool to determine the scattering matrix to characterize the wave diffraction at the corner.

In practice, waveguide systems usually have continuous corners. Felix and Pagneux [10] proposed a multimodal approach to analyze the sound propagation in a waveguide with continuous bends. However, the acoustic characteristics of bends (with finite constant curvature) differ substantially from those sharp corners. For an acoustic ventilation window, the ventilation path can also be regarded as a waveguide with continuous corners. Kang and Brocklesby [11] studied acoustic ventilation windows in an experimental way, but his work focused on the effect brought by the micro-perforated plat (MPP) inline.

Guided by previous studies [1–11], this paper further investigated the acoustic wave propagation in a waveguide with continuous right-angled corners numerically and experimentally, with the physical interpretation on the effect brought by the corners. It is noticed that, in the present study, a waveguide with continuous right-angled corners merely refers to a waveguide with two corners. However, it is straightforward to extend the current study to investigate the performance of a waveguide with multiple corners. For a waveguide with two corners, its acoustic performance is not simply a "summation" of two individual single-cornered ones. It can be imaged that the overall performance of the waveguide varies with the distance between the corners. Therefore, the emphasis of the present study is focused on the effect brought by the distance between the corners. The modeling of the waveguide system is described in Section 2. Section 3 presents the acoustic performance of the waveguide with a single right-angled corner. The performance of a multi-cornered waveguide is investigated

* Corresponding author. Tel.: +86 021 6598 2313.
E-mail address: zxjiang@tongji.edu.cn (Z. Jiang).

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numerically in Section 4. In Section 5, the experimental measurements are reported. Finally, the discussion and conclusion are made in Section 6.

2. Modeling of the waveguides

Fig. 1(a) shows a three-dimensional waveguide system with a right-angled corner. For a time harmonic excitation, the sound pressure field can be described by a two-dimensional inhomogeneous Helmholtz equation with the time-dependent term $e^{j\omega t}$ omitted:

$$\nabla^2 p + k^2 p = -\rho Q \quad (1)$$

where ∇^2 is the Laplace operator, ρ is the air density, and Q is the source strength. In Eq. (1), k is the wave number, which equals to the angular frequency ω divided by the speed of sound (i.e. $k = \omega/c$). In a straight rigid-walled duct along x-axis, the two-dimensional solution (assuming that sound pressure is constant along the z-axis) to Eq. (1) is

$$p = A_0 e^{-jkx} + \sum_{n=1}^{+\infty} A_n \cos(k_n y) e^{-j\sqrt{k^2-k_n^2}x} + B_0 e^{jkx} + \sum_{n=1}^{+\infty} B_n \cos(k_n y) e^{j\sqrt{k^2-k_n^2}x} \quad (2)$$

which is the superposition of different wave modes. The first two terms in Eq. (2) represent the plane and higher-ordered waves

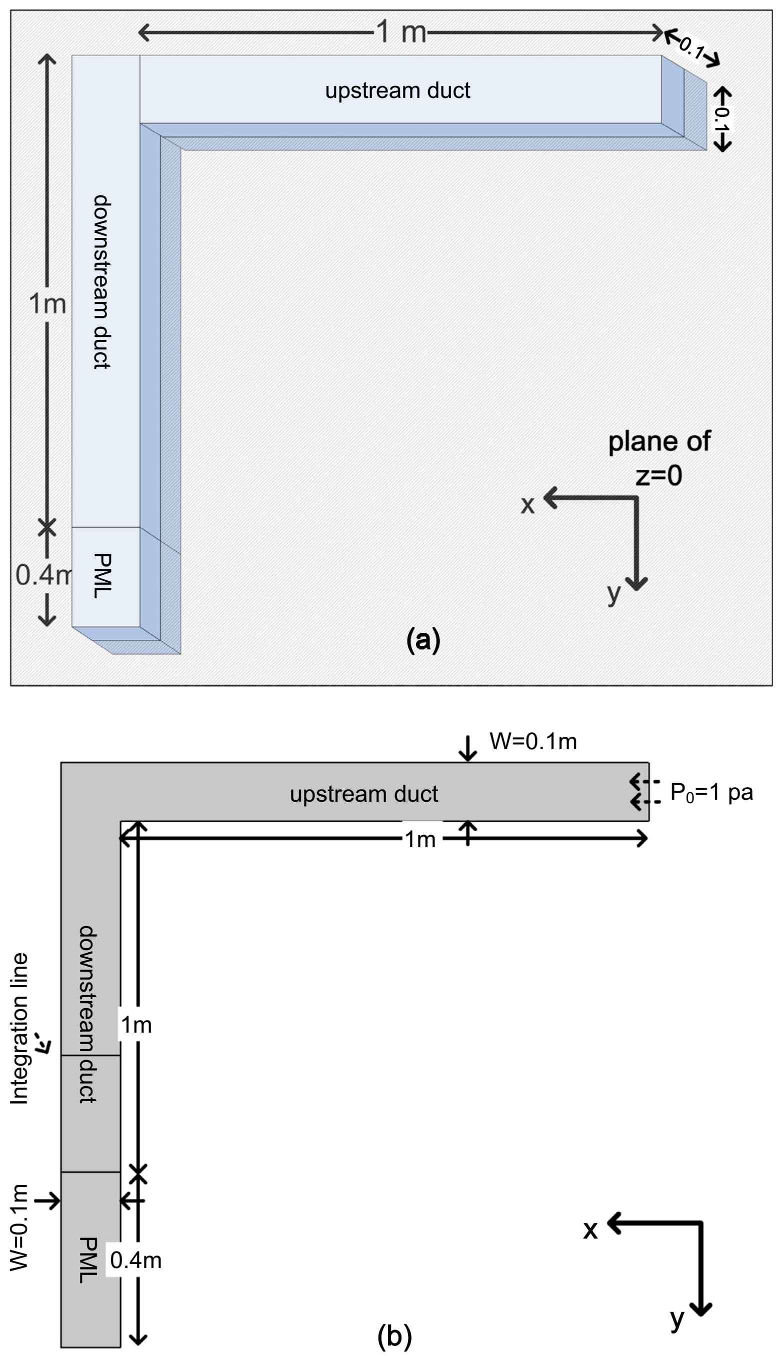

Fig. 1. (a) Geometry of a three-dimensional waveguide model with a single corner; (b) the sectional view of the single-corner waveguide.

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