Applied Acoustics 139 (2018) 213–221

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Experimental and numerical investigation of anechoic termination for a duct with mean flow

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ARTICLE INFO

Keywords:
Anechoic termination
Flow duct
Finite element model

ABSTRACT

For many in-duct aero-acoustic test systems, non-reflecting condition is assumed on one end or both ends for the test and analysis of the inner acoustic field, which may be physically realized by using anechoic terminations. Thus, it is of interest to investigate the performance of anechoic terminations under different flow conditions. In this paper, the performance of a typical two-sided anechoic termination of a flow duct is experimentally investigated, where the sound pressure reflection coefficient is the most important acoustic quantity. And a finite element model is established to predict the pressure reflection coefficient of the anechoic termination in the presence of flow. Effects of the inside partition plates, the shape of expansion and the absorbing materials are both experimentally and theoretically considered. Numerical predictions show good agreement with experimental results. It is shown that the resonant behavior of the anechoic termination may result in local minimums in the pressure reflection coefficient at low frequencies. The mean flow has little effect on performance of the anechoic termination except for the frequency range from 0.4 to 1.0 kHz, where the pressure reflection coefficient with flow is slightly larger than that without flow. The partition plates inside the expanding area of the anechoic termination cause improper scatterings of sound intensity inside the termination leading to undesired increases of the pressure reflection coefficient between 2 kHz and 3 kHz. The results presented in this paper may lead to further work towards the optimal design of continued anechoic terminations for different aero-acoustic test facilities.

1. Introduction

Anechoic terminations are assemblies connected to duct end functioning to transform a duct of finite length into an acoustically infinite long duct to provide a non-reflecting termination for many in-duct aero-acoustic measurements, for example the sound-power measuring systems [1–5] and the liner impedance eduction techniques [6–9]. Many analytical and numerical studies on duct acoustics also rely on the anechoic assumption to provide a convenient basis for modelling [10–11], which may be physically realized by a well-designed anechoic termination. However, in reality an accurate non-reflecting condition is impractical to be rigorously achieved, particularly at very low frequencies where the large wavelengths require excessive size of the termination. Both acoustic measurements and theoretical models which are based on this assumption may sustain great errors when the duct end is quite reflective. Therefore, effectiveness of an anechoic termination should be carefully examined to ensure the anechoic assumption.

To suppress the reflection of sound waves back into the duct, the primary factor that contributes to the design of an anechoic termination is a sufficiently gradual change of the acoustic impedance along the termination. And designs of anechoic terminations are quite different whether the flow is present in the duct or not. When the flow is absent, wedges and single-or-multiple layer absorbing materials, which are usually used for constructing an anechoic chamber, can be readily used to design an anechoic termination [12,13]. However, for ducts with flow, e.g., the HVAC (heating, ventilation and air conditioning) systems [14], the sound-power measuring systems [1–5] and grazing flow facilities for liner impedance measurements [6–9], effects of flow on the acoustical performance of an anechoic termination should be considered, as the anechoic termination is required to achieve a sufficiently low pressure reflection coefficient at different flow velocities and the termination should not obstruct the flow, i.e., should not generate noise.

Several kinds of anechoic termination for flow ducts have been developed in the public literatures [1–9,14–18]. The most common design is the anechoic termination with gradually and continuously expanding cross-section, which usually approximates an exponential or

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https://doi.org/10.1016/j.apacoust.2018.05.009
Received 23 November 2017; Received in revised form 25 April 2018; Accepted 4 May 2018

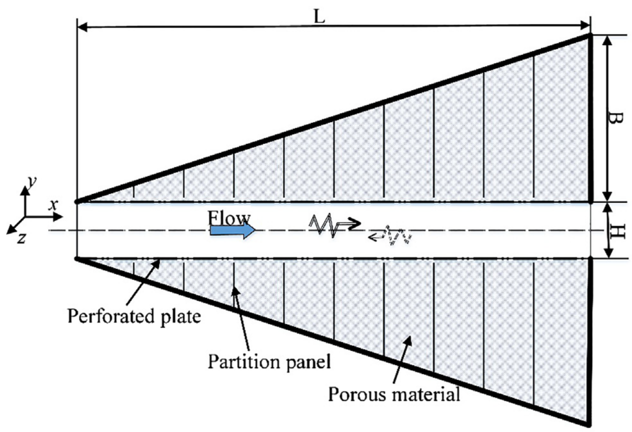

Fig. 1. Configuration of the anechoic termination.

Table 1
Geometric parameters of the perforated plate.

Diameter d (mm)	Thickness t (mm)	Porosity σ
1.0	1.0	0.1

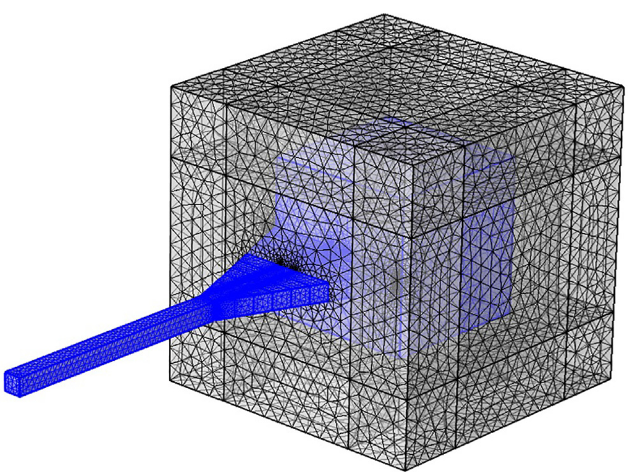

Fig. 2. Overview of the computational domain.

a Catenoidal horn to ensure the continuity of acoustic impedance along the termination. The expanding region is filled with absorptive materials or structures to provide attenuation for sound power, such that the free cross-sectional area for mean flow is constant or slowly expanding in the axial direction. A typical example of this kind of anechoic termination is the one-or-two sided termination designed by Neise [5,15] and developed in many aero-acoustic test facilities [17–18]. The expanding region of the anechoic termination is piecewise linear, approximately equal to that of an exponential horn, in which mineral wool with pockets of empty space is arranged. Detail of this design is depicted in the ISO 5136 standard [19], where several other recommendations on the anechoic termination design are also given. These designs can be practicable if the dimensions are suitable, but considerable scaling is discouraged to design anechoic terminations of different sizes. Besides, to the best of the author's knowledge, very limited analytical or numerical researches on this kind of anechoic termination are available to provide an assessment of the termination design for different test facilities before manufacture.

The most important parameter for assessing the performance of an anechoic termination is the sound pressure reflection coefficient, which is defined as the ratio of the sound pressure of the sound wave reflected from the anechoic termination to that of the incident wave. Both experimental evaluation and numerical prediction on the pressure reflection coefficient of a two-sided anechoic termination prototype of a flow duct have been carried out in this paper. In Section 2, a finite element model based on the commercial software, COMSOL Multiphysics, is set up to simulate the acoustic behavior of the anechoic termination. Detailed description of the experimental sets and methods are available in Section 3. The two microphone technique [20] is used to determine the pressure reflection coefficient of the anechoic termination, and the two-load method [21] is used to obtain the equivalent parameters of the porous media inside the anechoic termination. Section 4 gives the results and discussions. Attentions have been paid on effects of several design factors on the performance of the anechoic termination. Finally, conclusions of this paper are given.

2. Theoretical model

As shown in Fig. 1, the present model considers a three-dimension flow duct with a two-sided anechoic termination. The cross-section of the duct is square with side length $H = 51$ mm. Length of the anechoic termination along the axial direction is $L = 500$ mm, and the mouth half width is $B = 200$ mm. The anechoic termination has continued expanding cross-section in which porous material is filled; to achieve more absorption of the sound power, the expansion is subdivided into twenty equally spaced and locally reacting cells by eighteen partition plates. Two perforated plates are mounted along the upper and lower wall of the duct section. Parameters of the perforated plate are shown in Table 1, which are designed not only to protect the porous material but also to provide additional acoustic resistance. Apart from the perforated plates, walls of the anechoic termination together with the partition plates are rigid.

Under the assumption of harmonic time dependence, $\exp(i\omega t)$, and uniform mean flow, the acoustic field in the duct section of the anechoic termination can be described by the linearized potential flow equation [22]:

$$\nabla^2\varphi-\frac{1}{c_0^2}\left(-\omega^2\varphi+2i\omega U\frac{\partial\varphi}{\partial x}+U^2\frac{\partial^2\varphi}{\partial x^2}\right)=0 \tag{1}$$

where φ is the perturbation velocity potential, c_0 is sound speed of the air and U is the averaged flow velocity in the duct.

The porous material is assumed as a solid, homogeneous and isotropic media, and hence it can be modeled as an equivalent fluid with specific damping properties, i.e., characteristic impedance Z_p and complex wave number k_p, which are determined experimentally (see Section 3.2). Thus, the sound propagation in the porous material can

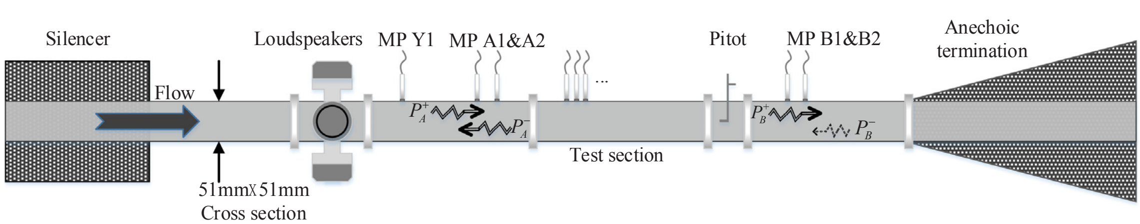

Fig. 3. Schematic of the aero-acoustic test rig.