Applied Acoustics 141 (2018) 362–370

Contents lists available at ScienceDirect

Applied Acoustics

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

Experimental study on the comprehensive performance of the application of U-shaped corrugated pipes into reactive mufflers

Fei Xue, Beibei Sun*

School of Mechanical Engineering, Southeast University, Nanjing, Jiangsu Province 211189, China

ARTICLE INFO

Keywords:
U-shaped corrugated pipes
Reactive muffler
Cutoff frequency
Noise reduction
Whistling noise
Airflow velocity
Improvement coefficient

ABSTRACT

Reactive muffler is widely used to reduce the low-frequency noise generated by internal combustion engines. Though researchers have put forward the methods to optimize the performance of muffler recently, it is often difficult to obtain ideal noise reduction performance in the high-frequency range. This paper presents an experimental study on the comprehensive performance of the application of U-shaped corrugated pipes into a simple expansion chamber muffler, which is aimed to optimize the noise reduction performance over the upper cutoff frequency range for the reactive mufflers. Then, the noise reduction performance and aerodynamic performance are experimentally evaluated. Subsequently, the experimental results of the muffler with corrugated pipes are analyzed and compared to that of the muffler with insertion pipes. Furthermore, improvement coefficient η is proposed to evaluate the comprehensive effect of U-shaped corrugated pipes on the noise attenuation and aerodynamic performance. Results demonstrate that the application of corrugated pipes in reactive muffler significantly improves the noise reduction performance above the upper cutoff frequency range. Besides, the insertion loss of the muffler with corrugated pipes is 4.0–4.3 dB(A) higher than the muffler with insertion pipes. Moreover, the improvement coefficient η reaches 1.12–1.13, indicating the corrugated pipes make more contribution in noise reduction than in pressure loss. Furthermore, the whistling frequency is not observed at different airflow velocities, indicating the corrugated pipes are probably unlikely to generate the whistling noise. What's more, it is observed that the muffler with corrugated pipes have a better ability of lowering the regenerative noise in low frequency than the muffler with insertion pipes. In conclusion, this study verifies that the application of U-shaped corrugated pipes into reactive mufflers is feasible and acceptable, and it provides a novel method in the acoustical design of reactive mufflers.

1. Introduction

As is known that mufflers are widely used to reduce the intake and exhaust noise. And a reactive muffler is preferred to reduce the low frequency noise generated by internal combustion engines. The main goal of the exhaust muffler design is to maximize the transmission loss at a target frequency and minimize the pressure loss simultaneously [1]. Due to the space limitation of the structure, structural parameters of the prototype muffler are usually determined according to engineering experiences, and then through the method of orthogonal experiment to achieve muffler optimization. However, this method is often difficult to obtain global optimal solution.

In recent years, researchers have put forward the methods to optimize the muffler performance to maximize the transmission loss at a target frequency and minimize the pressure loss. Khamchane [2] combined the improved four-pole transmission matrix method and shape optimization, aiming to maximize the transmission loss values of the target frequency. Chiu [3] predicted the transmission loss of the multi-cavity muffler using the GA and simulated annealing algorithm, based on the theory of one dimensional plane wave and four-port transmission matrix method. Lee [4–6] described in detail a gradient optimization algorithm, and combined it with the topology optimization to search the layout of the internal muffler structure. Siano [7] used a multiobjective topology optimization method to maximize the transmission loss at a target frequency and minimize the pressure drop simultaneously. Xiang [8,9] tried to use the combination of perforated tubes and expansion chamber to achieve the wide-band noise reduction performance through the optimization of structural parameters. Yu [10], Ouédraogo [11], Sagar [12], Oh S [13], Fan [14] et al, tried to use the combination of perforated tubes and expansion chamber to achieve the muffler wide-band muffler performance through the optimization of structural parameters. However, these optimization methods have no

* Corresponding author.
E-mail address: bbsun@seu.edu.cn (B. Sun).

https://doi.org/10.1016/j.apacoust.2018.07.021
Received 5 March 2018; Received in revised form 26 June 2018; Accepted 17 July 2018

obvious effect on improving the noise reduction performance above the upper cutoff frequency range of the reactive muffler, and usually these improvements will bring a significant increase in pressure loss, which will further increase the power consumption of the engine. Although the parameter optimization of the perforated tubes can improve the noise reduction within the frequency band above the cutoff frequency to a certain extent, it also increases the volume and pressure loss of the muffler. Therefore, a new acoustic element needs to be studied to meet the requirements of higher noise reduction, lower backpressure (pressure loss) and smaller muffler volume. Recently, Xue and Sun [15] studied the influence of structural parameters on the transmission loss of U-shaped corrugated pipe by using the Finite Element Method (FEM), and it is found that the U-shaped corrugated pipes have a good ability of noise reduction in the middle and high frequency band [15]. Therefore, if the corrugated pipes are properly designed, the problem of insufficiency in noise reduction over the upper cutoff frequency range of reactive muffler will be solved.

However, in the work of Xue and Sun [15], the influence of airflow on the noise generation was not taken into accounted. In the past decades, researchers found that the loud and clear tonal noises, also known as “whistling noise”, would be generated by corrugated pipes with air flowing through the pipes [16]. Large amount of work has been done on the whistling noise generated by airflow in corrugated pipes. Crawford [17] first applied the Bernoulli’s principle into explanation and prediction for the whistling noise, and this theory works well for the whistling of rotating musical toys. Nakiboğlu [18,19] proposed a new model to better capture the flow physics aspect of the rotating corrugated pipe. Cummings [20] proposed a simple model for the acoustics of corrugated pipes with airflow, and it explains the reason for reduced resonant frequency in a corrugated pipe compared to a smooth pipe. In addition, the Energy Balance Model (EBM) [18,21], Semi-empirical Model for Aeroacoustic Interaction (SMAI) [22], Plane Wave Acoustic Model (PWAM) [23] were also established to predict the whistling frequency and sound pressure amplitude. In other aspects, Nakiboğlu [18,19], Rajavel [24,25], Golliard [26], and Popescu [27] et al, carried out a series of numerical studies on the prediction of whistling frequency of different corrugated pipes. However, similar to the various theoretical models such as EBM and PWAM, the prediction of sound pressure level using FEM simulation is also not accurate [28]. Hence, it can be concluded that when applying the corrugated pipes into reactive mufflers, the influence of airflow on the noise generation, as well as the noise reduction performance and the aerodynamic performance, should not be neglected.

Therefore, based on the work of Xue and Sun [15], this paper presents an experimental study on the comprehensive performance of the application of U-shaped corrugated pipes into reactive muffler when the airflow in pipes is considered. The physical model of U-shaped corrugated pipe is shown in Fig. 1 [15], where h_c is the corrugation height, l_c is the corrugation length, d_{in} is the corrugation internal diameter, w_s is the corrugated trough width, and N is the total corrugation number. Fig. 1(b) shows different kinds of metal corrugated pipes in practical applications. The paper is organized as follows. The next section presents theoretical formulations on the acoustic models for the whistling frequency and cutoff frequencies of corrugated pipes. Section 3 describes a case study model and experimental setup used in this paper. In Section 4, the experimental results are analyzed and discussed. Finally, in Section 5, the conclusions are summarized with a discussion of future work.

2. Theoretical formulations

2.1. Theory of sound generation in corrugated pipes

Bernoulli’s Principle for Corrugated Pipes. For an ideal open-ended pipe, the whistling frequency can be expressed as [24,28]:

$$f_n = \frac{nc}{2L}, \quad \text{for } n = 1, 2, 3..., \tag{1}$$

where, c is the sound velocity and L is the total length of the corrugated pipe. Since the air is moving in and out of the corrugated pipe, the effective length L_e should be used instead of L. The effective length L_e is given by [24,28]:

$$L_e = L + 1.2r, \tag{2}$$

where, r is the internal radius of the corrugated pipe.

Cummings Acoustics Model for Corrugated Pipes. The whistling frequencies prediction model of the corrugated pipe establishes by Cummings is expressed in Eq. (3) [24,28]. In Cummings’ model, he assumed that the effect of the corrugation cavities was similar to the compressible [24,28]. In addition, he also supposed the corrugations were rectangular cylinders,

$$f_n = \frac{nc}{2L_e}\frac{(1-M^2)}{\left[1+\frac{d_c}{r}\left(\frac{l_c}{p_c}\right)\left(1+\frac{d_c}{2r}\right)\right]}, \quad \text{for } n = 1, 2, 3, ..., \tag{3}$$

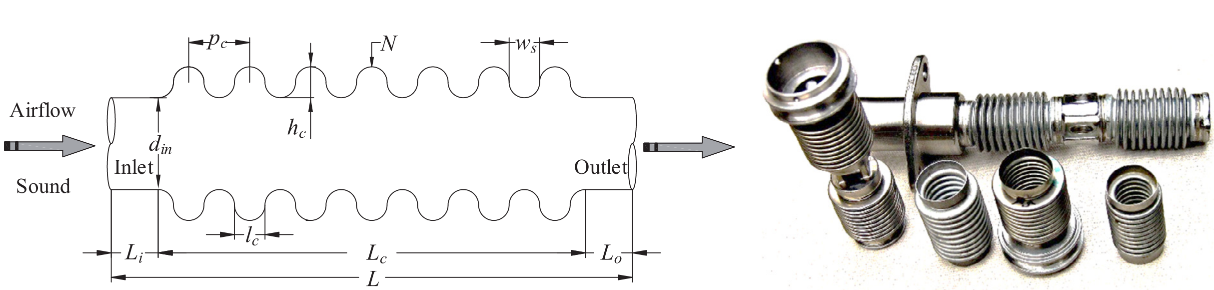
where M is the Mach number, r is the inside radius, l_c is the cavity length, d_c is the cavity depth, and p_c is the corrugation pitch. Cummings also found that if$M^2 \ll 1$, then the Eq. (3) can be approximated as [24,28]:

$$f_n \approx 0.89\frac{nc}{2L_e}, \quad \text{for } n = 1, 2, 3..., \tag{4}$$

Binnie Acoustics Model for Corrugated Pipes. Binnie proposed a model to predict the whistling frequency in a corrugated pipe, and he modeled the corrugated pipe as a Helmholtz resonator, as shown in Eq. (5) [24,28]:

$$f_n = \frac{nc}{2L_e}\frac{1}{\sqrt{1+\frac{V_c}{Ap_c}}}, \quad \text{for } n = 1, 2, 3..., \tag{5}$$

where V_c is the corrugation volume, A is the corrugation area to the tube ($A = 2\pi rl_c$) and p_c is the corrugation pitch.



(a) Geometric model (b) Metal corrugated pipes

Fig. 1. U-shaped corrugated pipe.