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Effect of extended necks on transmission loss performances of Helmholtz resonators in presence of a grazing flow

He Zhao [a], Zhengli Lu [a], Yiheng Guan [a], Zhiqiang Liu [b,*], Guoneng Li [c], Jun Liu [d], C.Z. Ji [a,e,**]

[a] *School of Energy and Power Engineering, Jiangsu University of Science and Technology, Zhenjiang City, Mengxi Road 2, Jiangsu Province 212003, China*
[b] *College of Automotive and Mechanical Engineering, Changsha University of Science and Technology, YuHua District, Changsha City, 410114, Hunan Province, China*
[c] *School of Mechanical and Automotive Engineering, Zhejiang University of Science and Technology, Hangzhou City, Liuhe Road, Zhejiang Province 310023, China*
[d] *Jiangsu Jintongling Fluid Machinery Technology Co. Ltd., No. 135 Mid Zhongxiu Road, Nantong City, Jiangsu Province 226001, China*
[e] *College of Engineering, Nanyang Technological University, 639798, Singapore*

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ABSTRACT

Suppressing acoustic pulsations is a critical task in modern premixed combustion-involved gas turbines. As a classical acoustic noise damper, Helmholtz resonator is generally applied in gas turbine combustors to reduce the transmission of acoustic perturbations. However, the neck configuration of a Helmholtz resonator may be designed in different ways. To obtain an optimum design and to compare the noise damping performances of these different configurations of the resonator necks, comparison study is conducted via developing a 2D linearized Navier–Stokes model of a duct in the presence of a grazing flow. A Helmholtz resonator is implemented on the duct as a side branch. The model is in frequency domain and it is validated first by comparing the numerical results with the experimental measurements available in the literature. The effects of 1) 3 extended neck configurations, 2) extended neck length and 3) the grazing flow Mach number are evaluated. It is shown that higher Mach number of the grazing flow, lower transmission loss. As the extended neck is in different configurations, the resonant frequencies and the maximum transmission losses are dramatically different, especially as the grazing Mach number M_u is greater than 0.05, i.e. $M_u \geq 0.05$. Approximately 20% resonant frequency shift is observed. The conventional design of Helmholtz resonator without an extended neck is found to perform much less effective than that of with concentric extended neck. The optimum design of the resonator neck can lead to 5–11 dB more transmission loss over a broader frequency range, especially at higher Mach number. The noise damping mechanism is visualized by the formation of vortex shedding at the neck of the resonator and sound energy is converted into kinetic energy being dissipated by the surrounding air. The present work opens up a predictive means to optimize the design of a Helmholtz resonator.

1. Introduction

To passively absorb unwanted broadband or tonal noise in gas turbine engines or ducts, Helmholtz resonators are commonly applied [1–3]. In gas turbines, Helmholtz resonators are applied in combustors in presence of a grazing flow to attenuate thermoacoustic instability [4–6]. Helmholtz resonators are applied to significantly attenuation these acoustic pulsations and certain amplitude pulsations are tolerable in engines [4,1]. A Helmholtz resonator [7] consisting a cavity is connected to a combustor via a short tube (also known as neck). Incident acoustic fluctuations may excite the cavity air–neck mass to oscillate, depending on the geometric dimension of the neck and the cavity, which is analogy to spring-stiffness system [8]. The excitation thus enables acoustic attenuation being achieved via vortices generation and thermo-viscous effect [9]. This is one of the noise damping mechanisms of Helmholtz resonator.

Extensive research and analysis relating to the design, characterization, implementation and the acoustic impedance, power absorption, transmission loss of a Helmholtz resonator have been conducted [10,4]. Bellucci et al. [4] developed a nonlinear model to predict the resonator impedance and acoustic power absorption to capture the nonlinear damping mechanism. The model is validated by a well-designed atmospheric experiment in the absence

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[*] Corresponding author.
[**] Corresponding author at: School of Energy and Power Engineering, Jiangsu University of Science and Technology, Zhenjiang City, Mengxi Road 2, Jiangsu Province 212003, China.
E-mail addresses: lzq0228@126.com (Z. Liu), czJi1000@gmail.com (C.Z. Ji).

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of a grazing flow. A Helmholtz resonator [11,12] implemented in engines or ducts is associated with a high acoustic impedance to acoustic disturbances propagating at its natural resonant frequency. Thus the incident acoustic waves will be effectively blocked and lead to a large transmission loss. Tournadre et al. [13] conducted incompressible CFD studies to predict the acoustic impedance of Helmholtz resonator. However, the results are overpredicted in comparison with fully compressible studies. Bothien & Wassmer [14] experimentally examine the effect of density discontinuities on the resonance frequency of Helmholtz resonators. This experimental flow conditions mimic the real engines [15]. Sohn et al. [16] found out from a series of experimental measurements that the effectiveness of the Helmholtz resonator is limited to certain narrow frequency bandwidths. Recent studies [2,3,17,18] have shown that attenuating tonal acoustic noise of varying frequency can be maximized by actively or adaptively tuning the resonant frequency of the Helmholtz resonator. This is typically achieved by adjusting the resonator's geometric dimensions [3], such as the cavity volume, neck area, or neck length. As a mean flow is present, incident sound waves may cause unsteady vortex shedding at the edge of the neck [19,20]. This vortex is then swept away by the mean grazing flow and behave like a source to the incident sound near the upstream edge.

The theoretical derivation of the resonant frequency of Helmholtz resonator was done long time ago. However, the noise damping mechanism especially in the presence of a hot or cold grazing flow [21] (tangential flow over the resonator) are still not thoroughly understood. Cosic et al. [9] conducted experimental visualization and measurement of a Helmholtz resonator in the presence of a hot grazing flow. The acoustic response of the resonator is measured in the linear and nonlinear amplitude regime. Dai [22] numerically study the effect of convected vorticity on exciting a Helmholtz resonator. Ghanadi et al. [21] experimentally study the response characteristics of the Helmholtz resonator in a subsonic wind tunnel, as a grazing flow is fully developed in to turbulence. It is found that resonator geometry determines the degree of excitation of acoustic pressure and velocity.

Selamet and Lee [7,23–25] conducted a series of theoretical, numerical and experimental studies on circular symmetric and asymmetric Helmholtz resonators in the absence of a grazing flow. The effects of perforated orifices with and without absorbing materials on the neck were examined. Further studies were conducted on a Helmholtz resonator with an extended neck [23]. The shapes and lengths of the extended neck are found to influence the transmission loss and resonance frequency. Experimental studies were performed by using an impedance tube. And the theoretical and numerical studies were achieved by using piston-driven model and boundary element method. However, this theoretical and numerical analyses are not able to capture and predict the effect of a mean grazing flow [26], which is typically expected in practical applications. This partially motivated the present work.

The preceding researches show that the noise damping performance and vorticity-involved mechanism of coupled Helmholtz resonators are studied by modelling in time-domain via solving nonlinear Navier–Stokes equations [27,28], or conducting laser-involved flow and acoustic visualization experiments. These numerical and experimental studies are costly and time-consuming. To reduce computational cost and predict the noise performance and mechanism of coupled Helmholtz resonators, computational efficient 2D/3D models are needed. To the best knowledge of the authors, there are few numerical and experimental studies reported in the literature. This partially motivate the present research.

In this work, we propose a linearized Navier–Stokes equation approach. It is modelled in frequency domain and able to predict the acoustic damping performances of Helmholtz resonators with extended necks in 3 different configurations, as a grazing flow is present. The benchmark configuration is following the conventional resonator design. The other 2 configurations are associated with concentric neck in half or full extension. The developed 2D model is first validated with comparison with the experimental measurements in the literature. The paper is organized as follows. In Sect. 2, the linearized Navier–Stokes equations are derived in frequency domain. And the numerical models of the resonators with 3 different extended necks are described. In Sect. 3, the numerical results for are presented and compared with experimental ones over the frequency range from 50 to 200 Hz. The effects of 1) grazing flow Mach number and the configurations of the extended neck on the noise damping performances are evaluated over the frequency range of 50–200 Hz. Finally, the key findings on the Helmholtz resonators with extended necks are discussed and summarized in Sect. 4.

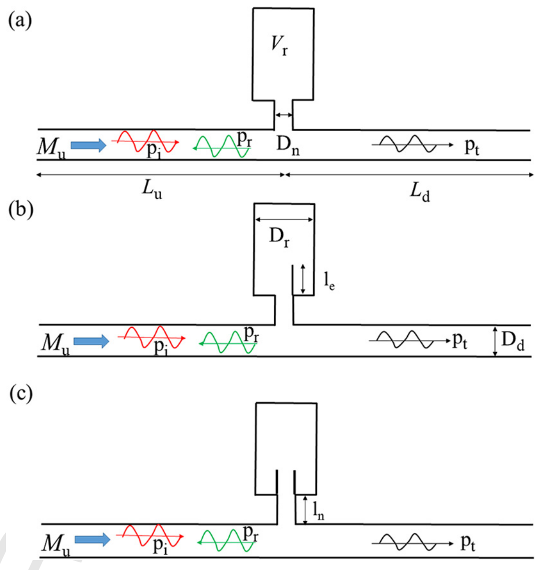

Fig. 1. Schematic drawing of the numerical models with 3 different extended neck configurations.

2. Description of the numerical model

The present work considers a cylindrical duct with a Helmholtz resonator attached as shown in Fig. 1. Here 3 different Helmholtz resonators without and with extended necks are modelled. Configuration a) represents the conventional design with no neck extension. Configurations b) and c) denote the resonators with partial or full extended neck. The governing equations are linearized Navier–Stokes ones [28] for viscous and compressible air flow. They include mass, momentum and energy conversion equations as given in a Cartesian coordinate system as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho_0 \vec{u} + \rho \vec{u}_0) = S_{ls} \qquad (1)$$

where S_{ls} denotes the acoustic perturbation generated from the loudspeaker. It is modelled as a monopole sound source to produce sinusoidal disturbances $S_{ls} = \sum_{n=1}^{N} \lambda_n \sin(\omega_n t)$ and $N = 31$. The perturbations are denoted by pressure, velocity, temperature and density (p, $\vec{u}$, T and ρ). Subscript 0 denotes the steady-state flow parameters.

The momentum equation is given as

$$\rho_0 \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u}_0 \cdot \nabla)\vec{u} \right] + \rho(\vec{u}_0 \cdot \nabla)\vec{u}_0 = \nabla \cdot \sigma - \vec{u}_0 S_{ls} \qquad (2)$$

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