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Control of low-frequency noise for piping systems via the design of coupled band gap of acoustic metamaterials

Yanfei Li [a], Huijie Shen [a,*], Linke Zhang [b], Yongsheng Su [a,*], Dianlong Yu [c]

[a] College of Power Engineering, Naval University of Engineering, Wuhan, 430033, China
[b] School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, 430063, China
[c] Key Laboratory of Science and Technology on Integrated Logistics Support, National University of Defense Technology, Changsha 410073, China

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ABSTRACT

Acoustic wave propagation and sound transmission in a metamaterial-based piping system with Helmholtz resonator (HR) attached periodically are studied. A transfer matrix method is developed to conduct the investigation. Calculational results show that the introduction of periodic HRs in the piping system could generate a band gap (BG) near the resonant frequency of the HR, such that the bandwidth and the attenuation effect of HR improved notably. Bragg type gaps are also exist in the system due to the systematic periodicity. By plotting the BG as functions of HR parameters, the effect of resonator parameters on the BG behavior, including bandwidth, location and attenuation performance, etc., is examined. It is found that Bragg-type gap would interplay with the resonant-type gap under some special situations, thereby giving rise to a super-wide coupled gap. Further, explicit formulation for BG exact coupling is extracted and some key parameters on modulating the width and the attenuation coefficient of coupled gaps are investigated. The coupled gap can be located to any frequency range as one concerned, thus rendering the low-frequency noise control feasible in a broad band range.

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1. Introduction

Piping systems have wide applications in many engineering applications, such as heat exchanger in chemical plants, ventilation and air condition in buildings, hot/cold leg pipes in nuclear steam supply systems, seawater pipes in ocean surface ships and underwater vehicles of which their outlets are underneath the water surface, *etc.* [1–3]. However, as the piping system begins to work, undesirable noise is produced, such that noise pollution is emitted and work environment is deteriorated. Hence, a considerable number of researches have been devoted to the noise reduction technologies for the piping systems [4–8].

One of the noise control methods that has been widely used in piping systems is the installation of water mufflers [9–13]. Acoustic wave transmitting in the pipe could be effectively attenuated if appropriate mufflers are employed, thus most of the noise emitted either from the outlet of piping system or from the pipe wall at downstream of muffler could be suppressed. Nevertheless, a limitation existing in the conventional mufflers is their control ability for the low-frequency noise. Take the common-used muffler of expansion-chamber type as an example, although it performs well for the noise reduction in the high frequency range, it loses out at low frequencies, except that its volume can be sufficiently large (this is always unpractical since the space left for anechoic devices to be installed in piping systems is so limited). The presence of Helmholtz resonator (HR) may help to solve the current problem of low-frequency noise control, yet its effective bandwidth of noise elimination turns out to be too narrow [14–17]. It is not surprising, therefore, that control technologies for low-frequency noise in piping systems have received a great deal of attention.

Recently, the emergence of artificially designed sub-wavelength acoustic materials/structures, referred to as acoustic metamaterials (AMs), provides a possible way to solve the sound and vibration problem encountered in industrial engineering [18–20]. AMs are generally regarded as artificial materials/structures with microstructures periodically embedded/attached that possess novel and unique properties, such as band gap (BG) [18–22], negative refraction [23–25], negative effective density and/or modulus [26–29], directional propagation [30], and so on [18,31]. The most important feature of AMs is its periodic structure. It is worth mentioning that the phenomenon of BG within which propagation of acoustic/elastic waves is stopped has triggered more exciting investigations on waveguide systems [18–22]. Early in 1998, Kushwaha et al. had confirmed the existence of complete acoustic BGs

* Corresponding authors.
E-mail addresses: shj588@163.com (H. Shen), suyongsheng1981@163.com (Y. Su).

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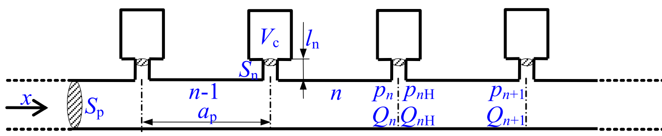

Fig. 1. Sketch of the piping system with HR attached periodically.

in a periodic system which is made up of several dangling side branches (DSB) periodically grafted at each of the equidistant sites on a slender tube [32]. Behind the work of Kushwaha et al., Boudouti et al. introduced a design of a simple acoustic filter consisting of two slender side tubes grafted periodically at two sites of an infinite slender tube, in which transmission gaps and Fano-like resonances are captured [33]. Examples of more recent studies may be appreciated from the works of Wang et al. [34,35] and Xiao et al. [36,37], who introduced the locally resonant structures into beams and pipes, and obtained elastic wave BGs in a much lower frequency range.

Generally, there are two formation mechanisms for the BGs: the Bragg scattering mechanism and the locally resonant (LR) mechanism. For the BGs induced by the Bragg scattering mechanism (defined as Bragg BGs), their central frequencies $f_{B,n}$ are governed by the Bragg condition $f_{B,n} = nc_0/2a$ $(n = 1, 2, 3\ldots)$, where c_0 and a are the wave speed of matrix material and the lattice constant, respectively [2,19]. This indicates that the dimension of the structure has to be sufficiently large if utilizing the Bragg BGs to insulate low-frequency noise. BGs produced by the latter mechanism (labeled as LR BGs) can be realized in a frequency range two orders of magnitude lower than those given by the Bragg limit, rendering the control of low-frequency noise with small size feasible. In the present work, the LR mechanism of AMs is introduced into the structure design for a piping system. The HR is employed as locally resonance that will be mounted periodically into the piping system. Under such a design strategy, the existence of LR BGs will be guaranteed. Bragg BGs do also exist in the same system due to the systematic periodicity. Unlike the previous studies, which were focused on the wave BG production and analysis, the emphasis here is placed on the exploration of the exactly coupling condition for Bragg and LR gaps in the periodic piping system, so as to achieve broadband acoustic gaps in the low frequency range. A transfer matrix (TM) method is developed in the paper, which is used to conduct the calculation of BGs and sound transmission loss (STL) [10]. Further, the exactly coupling condition is extracted and the effects of resonant parameters on the BGs are examined.

2. Governing equations and transfer matrix method

The piping system, consisting of a uniform pipe with HRs attached periodically, is sketched in Fig. 1. Volume of the HR cavity is V_c; l_n and S_n are respectively the length and the cross-sectional area of the neck; S_p is the cross-sectional area of the pipe. The connected HRs with appointed spacing a_p in the system are serving as localized resonators, thus such a construction can be viewed as a type of one-dimensional AM. Acoustic wave propagation in this system can be described by a plane wave assumption, as the audio-frequency noise the present work concerned is focused on the low frequency range.

Utilizing the time-harmonic acoustic equations of state simplified by suppressing the $\exp(-j\omega t)$ throughout, the scalar pressure p and vector fluid velocity v satisfy the following equations [23]:

$$\frac{\partial^2 p}{\partial x^2} + k^2 p = 0, \tag{1}$$

where k is the wave number that formulated by ω/c_0; ω and c_0 are respectively the radian frequency and the acoustic speed. Solution for the acoustic pressure within the pipe may be written in terms of positive and negative traveling waves, as follows:

$$p = A_t e^{jkx} + A_r e^{-jkx}, \tag{2}$$

wherein A_t and A_r denote the amplitude coefficients of transmitted and reflected waves, respectively. Utilizing the relation between sound press and acoustic velocity $v = -\rho_0^{-1}\int \partial p/\partial x dt$, where ρ_0 is the fluid density, the acoustic speed could be expressed as [23,34,35]:

$$v = \frac{1}{\rho_0 c_0}\left(A_t e^{jkx} + A_r e^{-jkx}\right) \tag{3}$$

and the volume speed Q as:

$$Q = \frac{S_p}{\rho_0 c_0}\left(A_t e^{jkx} - A_r e^{-jkx}\right). \tag{4}$$

Equations (1) and (2) may be seen to readily yield the following transfer matrix relation for a uniform pipe section with length of a_p:

$$\begin{Bmatrix} p_{nH} \\ Q_{nH} \end{Bmatrix} = \begin{bmatrix} \cos\frac{\omega a_p}{c_0} & j\frac{\rho_0 c_0}{S_p}\sin\frac{\omega a_p}{c_0} \\ j\frac{S_p}{\rho_0 c_0}\sin\frac{\omega a_p}{c_0} & \cos\frac{\omega a_p}{c_0} \end{bmatrix} \begin{Bmatrix} p_{n+1} \\ Q_{n+1} \end{Bmatrix}, \tag{5}$$

which can be rewritten into a short form by introducing the state vector $\mathbf{\Lambda} = \{p, Q\}'$, as follows:

$$\mathbf{\Lambda}_{nH} = \mathbf{T}_p \cdot \mathbf{\Lambda}_{n+1}. \tag{6}$$

Now, considering a connection point with a HR attached, the corresponding transfer matrix relation in terms of the classical state variables can be given by [34,35]

$$\begin{Bmatrix} p_n \\ Q_n \end{Bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/Z_H & 1 \end{bmatrix} \begin{Bmatrix} p_{nH} \\ Q_{nH} \end{Bmatrix}, \tag{7}$$

where Z_H is the acoustic impedance of HR, it can be formulated by a concentrated parameter model: $Z_H = j\omega L_H + (j\omega C_H)^{-1}$. Such a model is adequately correctly in capturing the acoustic characteristic of HR, as the dimension of HR is always smaller than the corresponding wavelength in low-frequency range. Equation (7) can be rewritten into the following abbreviated form:

$$\mathbf{\Lambda}_n = \mathbf{T}_H \cdot \mathbf{\Lambda}_{nH}. \tag{8}$$

Combining (6) and (8) yields

$$\mathbf{\Lambda}_n = \mathbf{T}_c \cdot \mathbf{\Lambda}_{n+1}, \tag{9}$$

wherein $\mathbf{T}_c = \mathbf{T}_H \cdot \mathbf{T}_p$, in fact, $\mathbf{T}_c$ is the transfer matrix for the state vectors at two ends of a periodic cell. Subscript 'n' indicates the relevant variables for the nth periodic cell. Due to the periodic boundary condition, the acoustic pressure and the volume speed in the left and the right side of a periodic cell should also satisfy the Bloch theorem [2,32,33,36,37], namely

$$\mathbf{\Lambda}_n = e^{j\mu a_p} \cdot \mathbf{\Lambda}_{n+1}. \tag{10}$$

Combined equations (9) with (10), yields the following equation:

$$\left|\mathbf{T}_c - e^{j\mu a_p}\mathbf{I}\right| = 0. \tag{11}$$

It follows the eigenvalues μ, as functions of ω, for the infinite periodic pipe system. The real part of μ is referred to as propagation constant or phase constant, and the imaginary part as attenuation constant (decay of the amplitude of a wave propagating from one cell to the following). It is can be known that wave propagation is possible within frequency bands where μ is real (pass bands), whereas attenuation occurs for the frequency values that provide an imaginary part to μ.

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