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RESEARCH ARTICLE

Numerical Analysis of Silencer with a Coiled Tube and Straight Perforated Tube Using FEM

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Abstract

Marine diesel engine is essential on a ship, but emits extremely loud noise harmful to human hearing. Therefore, it is mandatory to use silencers to reduce the venting noise of the marine diesel engine. An advanced silencer with a new acoustical element of a curved tube, along with perforated holes, is presented to suppress the noise wave. To predict the silencer's acoustical performance for high-order waves, a finite element model was built using COMSOL. The influence of the silencer's noise reduction ability was investigated by exploring sensitivity using acoustical simulations on COMSOL, regarding the silencer's geometric factors. The results proved that the silencer, featuring a perforated coiled tube and a perforated straight tube, is effective in noise elimination.

Keywords: Coiled, Straight, Perforated, FEM

1. Introduction

Sound is a disturbance that propagates through a medium (either fluid or solid) when a difference in pressure is created [1]. Improving the physical properties of the medium can effectively reduce noise energy. The acoustical performance of acoustical materials has been extensively studied since Delany and Bazley [2] began exploring the sound-absorbing coefficient of such materials in 1969. Further investigations into various factors that affect sound absorption ability were carried out. Johnson [3] identified four critical factors that influence sound absorption ability, including viscous character length, porosity, acoustic flow resistance, and curving. Sound-absorbing materials have been applied in sound attenuators to reduce noise. Rostafinski [4] recommended an acoustic model for estimating sound attenuation within a bent tube.

Fuller and Bies [5,6] studied the impact of various shapes of ducts and sections on acoustic efficiency. Kim and Ih [7] established a sound attenuation prediction system for a bent and extended cavity using a four-pole transfer matrix. Chang et al. constructed a multi-layer sound absorber for a constrained sound absorption system [8]. Later, they assessed the noise reduction of silencers with multiple bent tubes using neural networks in conjunction with the boundary element method and genetic algorithm [9]. To improve noise elimination ability, Chiu and Chang proposed a silencer consisting of a coiled perforated tube [10].

The studies mentioned above were conducted to address engineering problems related to noise. In the real world, marine diesel engines emit high levels of noise [11,12]. To ensure the hearing health of crew members, it is mandatory to use silencers to reduce the venting noise of marine diesel engines [13,14]. Chiu et al. [15] investigated the acoustical performance of optimally shaped circular silencers, internally hybridized with multiple reverse chambers, to account for the effect of higher-order waves. They used eigenfunction analysis in conjunction

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with the genetic algorithm to optimize the silencer design.

An advanced silencer with a coiled perforated tube and a straight perforated tube is proposed to improve the acoustical ability of silencers for reducing venting noise. To compare the noise reduction ability of the advanced silencer with a silencer that only has a coiled perforated tube, two types of silencers were explored and discussed (silencer A: a one-chamber silencer with a coiled/perforated tube and a straight/perforated tube; silencer B: a one-chamber silencer with only a coiled/perforated tube), as shown in Fig. 1. To account for the higher-order effect of a silencer with a complex geometric mechanism, FEM analysis (run on COMSOL) was used for acoustical prediction [16–18].

2. Mathematical background of the FEM (on COMSOL)

Two types of silencers were presented in Fig. 1: silencer A, which is composed of a coiled/perforated tube and a straight/perforated tube in a one-chamber configuration, and silencer B, which has only a coiled/perforated tube in a one-chamber configuration. The boundary condition of the solid boundary was expressed in the COMSOL acoustical model as follows.

$$n\cdot\left[\frac{1}{\rho_c}(\nabla p_t - q)\right] = 0 \tag{1}$$

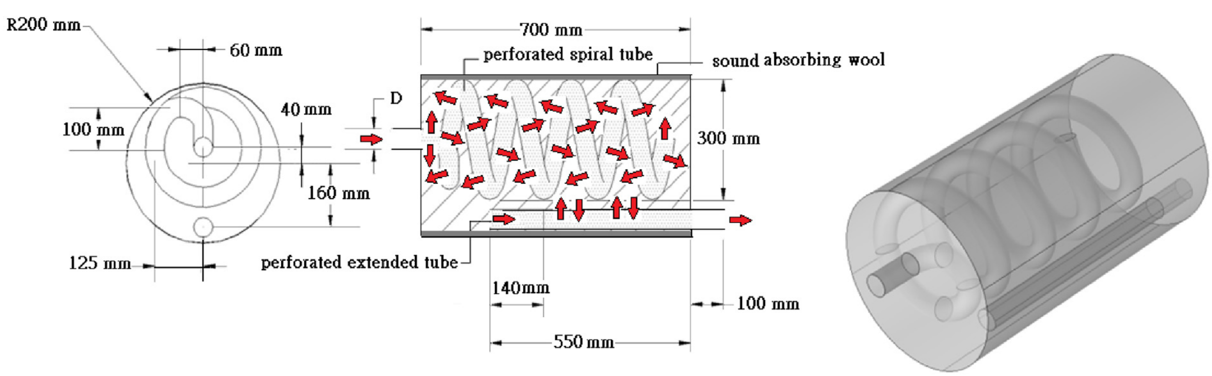
where $p_t = p + p_b$

Here, p_t is the sum of a possible background pressure p_b and the scattered pressure p. q is a dipole sound source.

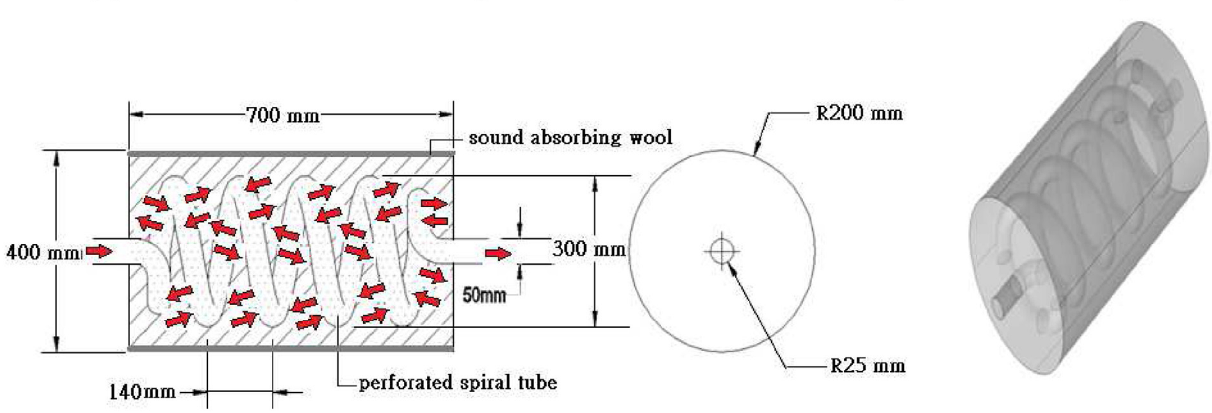
The perforated tube's boundary condition used in the COMSOL is

$$n\cdot\left[\frac{1}{\rho_c}(\nabla p_t - q)\right] = -(p_{t1} - p_{t2})\frac{j\omega}{Z_j} \tag{2}$$

$$Z_j = \rho_c c_c\left\{\frac{1}{\sigma}\sqrt{\frac{8\mu k}{\rho_c c_c}}\left[1+\left(\frac{t_p}{d_h}\right)\right] + \theta_f + j(t_p + d_h)\frac{k}{\sigma}\right\} \tag{3}$$



(a) Silencer A (silencer composed of coiled and extended perforated tubes)



(b) Silencer B (silencer composed of coiled perforated tube)

Fig. 1. Two acoustical mechanisms for silencer A and silencer B.

where ρ_c and c_c are complex-valued quantities, t_p, d_h, and σ are the thickness, the hole's diameter, and the perforation rate of the perforated tube, respectively; Z_j, μ, and k are the acoustical impedance, fluid viscosity, and wave number, also respectively. In addition, p_{t1} and p_{t2} represent the upstream pressure and downstream pressure, respectively.

Applying the Johnson-Champoux-Allard model in the porous material's acoustical simulation yields

$$\rho_{eff} = \alpha_\infty \rho_0 \left[1 + \left(\frac{\sigma_0 \varphi}{j\rho_0 \omega \alpha_\infty}\right) G_J(\omega)\right] \tag{4}$$

$$G_J(\omega) = \left[1 + \left(\frac{4j\alpha_\infty^2 \eta \rho_0 \omega}{\sigma_0^2 \cap^2 \varphi^2}\right)\right]^{1/2} \tag{5}$$

where φ and α_∞ represent the material's porosity and the curving level; η (shearing viscosity) is preset to be 1.84×10^{-5} (kg/m.s); and ω is the angular velocity. The σ_0 (flow resistivity) is expressed as

$$\sigma_0 = \frac{150\mu}{D_p^2 \varphi^3}(1-\varphi)^2 \tag{6}$$

Meanwhile, K_{eff} (the bulk factor) is

$$K_{eff} = \frac{\gamma P_0}{\gamma - (\gamma - 1)\left\{1 + \left[\frac{8\eta}{j\cap'^2 P_r \omega \rho_0}\left(1 + j\rho_0 \frac{\omega P_r \cap'^2}{16\eta}\right)^{1/2}\right]\right\}^{-1}} \tag{7}$$

where γ is the ratio of specific heats. P_0 is the quiescent pressure. Pr is the Prandtl number

Both ∩ and ∩′, representing viscous character length and thermal character length, are expressed as

$$\cap = \frac{1}{s}\left(\frac{8\tau_\infty \eta}{\sigma_0 \varphi}\right)^{1/2} \tag{8}$$

$$\cap' = \frac{1}{s'}\left(\frac{8\tau_\infty \eta}{\sigma_0 \varphi}\right)^{1/2} \tag{9}$$

where s is a pore geometry dependent factor between 0.3 and 3.0, and τ_∞ is the tortuosity factor (high frequency limit).

The sound wave equation moving through the silencer yields

$$\nabla \cdot \left[-\frac{1}{\rho_c}(\nabla p_t - q)\right] - \frac{k_{eq}^2}{\rho_c} p_t = Q \tag{10a}$$

where

$$k_{eq}^2 = \left(\frac{\omega}{c_c}\right)^2; \; c_c = c; \rho_c = \rho \tag{10b}$$

The Transmission Loss (TL) of sound is

$$TL = 10 \log \frac{W_{in}}{W_{out}} \tag{11}$$

3. Model verification

Silencers with three acoustical elements, including a straight perforated tube, extended tubes, and two-inlet tubes with one-outlet tube, were demonstrated in order to verify the accuracy of the COMSOL model and their performance was compared to experimental data. As shown in Fig. 2, the transmission loss (TL) curve of a silencer with a straight perforated tube was found to be consistent with experimental data [19], thus confirming the accuracy of the COMSOL simulation. Therefore, the COMSOL simulation was deemed satisfactory and utilized in the following sections.

4. Results and discussion

4.1. Results

Two types of one-chamber silencers, each internally fitted with different acoustic devices, were proposed. Silencer A contains a coiled/perforated tube along with a straight/perforated tube, while silencer B is fitted with only a coiled/perforated tube.

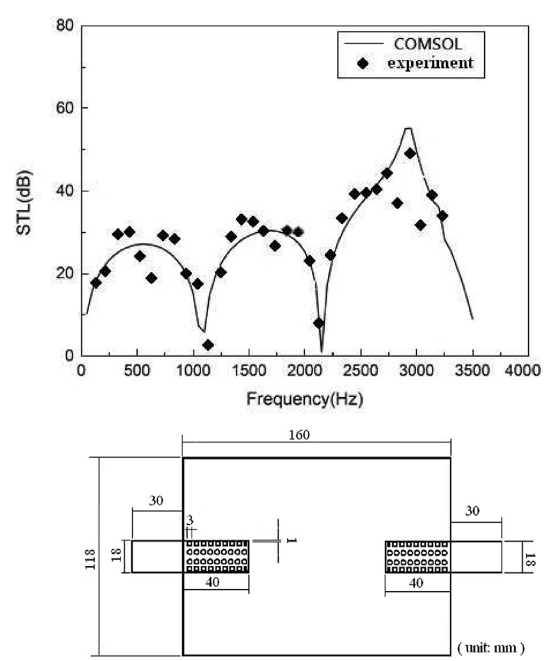


Fig. 2. Accuracy check of sound transmission loss for silencers internally inserted with extended tube [19].

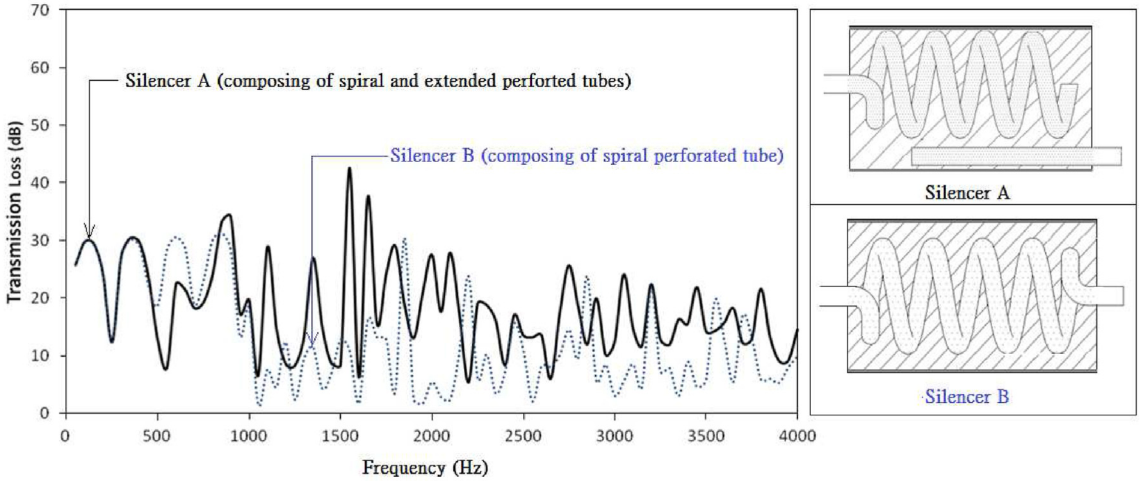


Fig. 3. The comparison of TL between silencer A and silencer B.

The comparison of transmission loss (TL) between silencer A and silencer B was conducted and is presented in Fig. 3. As depicted, the TL of silencer A is superior to that of silencer B, indicating that silencer A is a more effective device in mitigating venting noise. To investigate the impact of silencer A's geometric factors on TL, a sensitivity analysis for these factors was carried out.

The TL increases as the diameter (D) of the coiled perforated tube decreases, as shown in Fig. 4. Additionally, Fig. 5 demonstrates that the effect of TL related to the length (L) of the straight/perforated tube was noticeable when the frequency exceeded 1000 Hz. Furthermore, as illustrated in Fig. 6, the effect of TL on the perforation rate (σ) of both the coiled tube and perforated tube was significant when the frequency exceeded 500 Hz. Similarly, the impact of the acoustical flow impedance of wool (R) on TL, shown in Fig. 7, indicates that the TL curve will increase significantly as the acoustical flow resistance (R) increases.

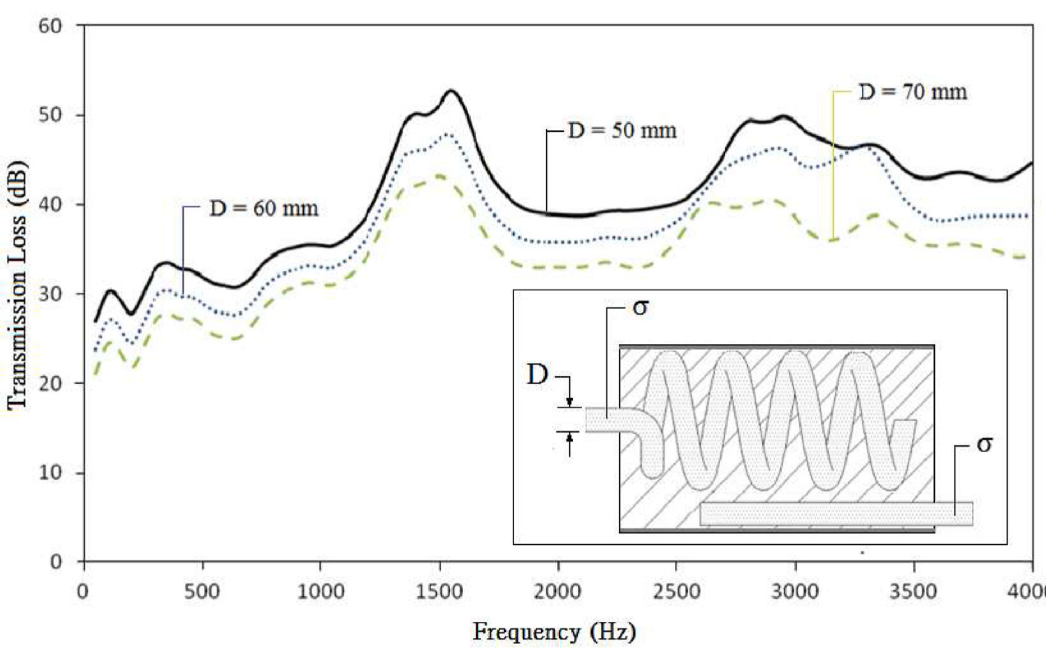


Fig. 4. The TL with regard to various values of parameter D at σ = 5%.

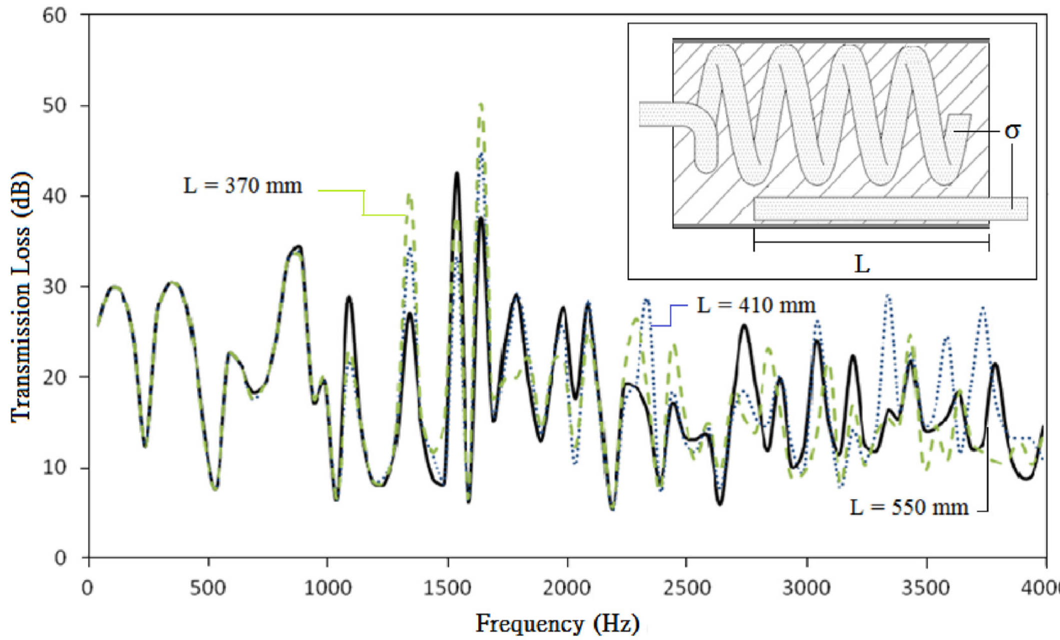


Fig. 5. The TL with regard to various value of parameter L at σ = 5%.

4.2. Discussion

The results presented in section 4.1 indicate the addition of the straight/perforated tube as an acoustical element in silencer A leads to superior acoustical performance compared to silencer B. To further investigate the influence of different geometrical factors (D, L, σ, and R) on the TL, acoustical simulations were performed. The results shown in Fig. 4 through Fig. 7 indicate that the TL of the silencer is inversely related to D and proportional to R. Thus, the acoustical effect of parameters D and R is consistent. However, the influence of TL with respect to L and σ is found to be fluctuating and inconsistent.

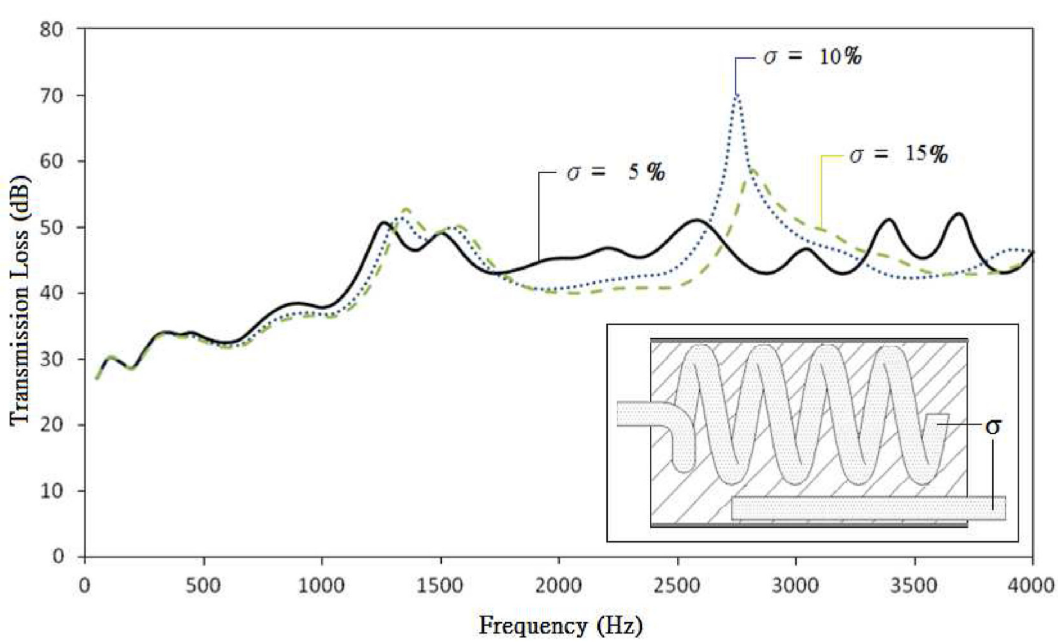


Fig. 6. The TL with regard to various value of parameter σ.

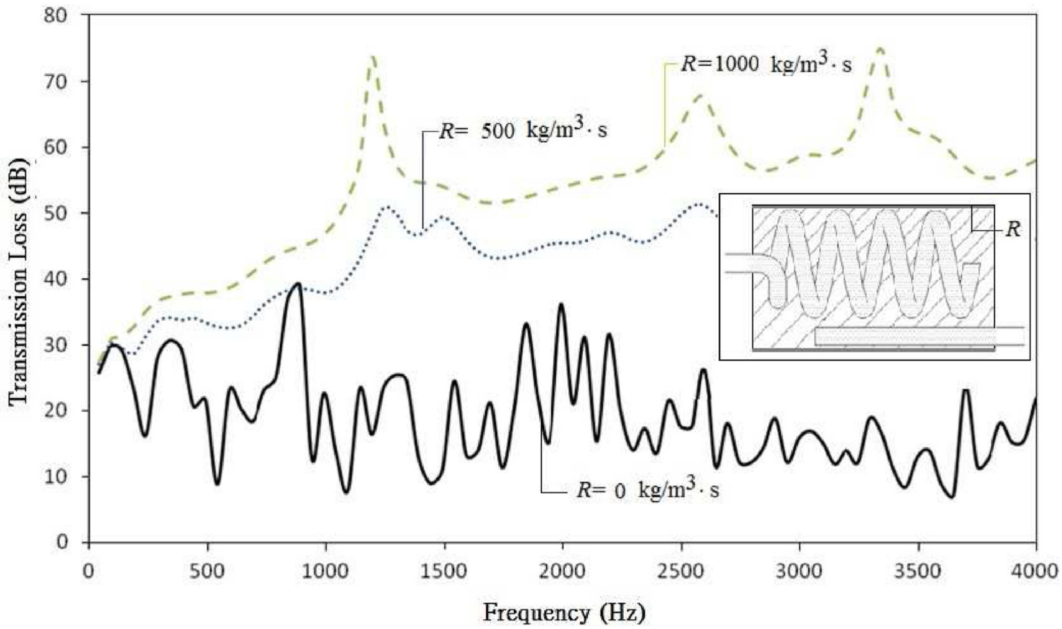


Fig. 7. The TL with respect to various value of parameter R (acoustical flow impedance of wool internally lined inside the shell's surface).

5. Conclusion

An advanced silencer with a new acoustical element of a curved tube in conjunction with perforated holes is proposed to effectively reduce the venting noise of marine diesel engines. Two types of one-chamber silencers are introduced, namely silencer A which includes a coiled/perforated tube and a straight/perforated tube, and silencer B which only contains a coiled/perforated tube. Acoustical simulations were performed, and the results show that silencer A outperforms silencer B in terms of acoustical performance. Additionally, the acoustical effect of TL with respect to the geometrical factors of silencer A has been evaluated. The simulated results demonstrate that the diameter of the coiled perforated tube (D) and the acoustic flow impedance (R) of the sound-absorbing material have a significant impact on the acoustical performance. The influence of TL with regard to the perforation rate on both the coiled tube and straight tube (σ) is noticeable when the frequency exceeds 500 Hz. Furthermore, the impact of TL regarding the length of the straight/perforated tube (L) is apparent when the frequency goes beyond 1000 Hz.

As a result, the acoustical investigation of silencer's geometric parameters presented in this paper can provide design principles for acoustic engineers when choosing acoustical elements and geometric parameters for silencer design.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

References

[1] Hansen CH. Fundamental of acoustics. Adelaide: University of Adelaide; 2001.
[2] Delany ME, Bazley EN. Acoustical properties of fibrous absorbent materials. Appl Acoust 1970;3(2):105–16.
[3] Johnson DL, Koplik J, Dashen R. Theory of dynamic permeability and tortuosity in fluid-saturated porous media. J Fluid Mech 1987;176:379–402.
[4] Rostafinski W. Transmission of wave energy in curved ducts. J Acoust Soc Am 1974;56:1005–7.
[5] Fuller CR, Bies DA. A reactive acoustic attenuator. J Sound Vib 1978;56(1):45–59.
[6] Fuller CR, Bies DA. Propagation of sound in a curved bend containing curved axial partition. J Acoust Soc Am 1978;63: 681–6.
[7] Kim JT, Ih JG. Transfer matrix of curved duct bends and sound attenuation in curved expansion chambers. Appl Acoust 1999;56:297–309.
[8] Chang YC, Yeh LJ, Chiu MC. Optimization of double-layer absorbers on constrained sound absorption system by using genetic algorithm. Int J Numer Meth Eng 2005;62: 317–33.
[9] Chang YC, Chiu MC, Wu LW. Shape optimization of mufflers hybridized with multiple connected tubes using boundary element method and neural networks and genetic algorithm. Proc. ImechE Part C: J Mech Eng Sci 2010;224(C4): 901–13.
[10] Chiu MC, Chang YC. Acoustical assessment of mufflers hybridized with spiral and extended tubes using finite element method, neural network model, and genetic algorithm. Build Acoust 2022;29(4):459–79.
[11] Bogdanowicz A, Kniaziewicz T. Marine diesel engine exhaust emissions measured in ship's dynamic operating conditions. Sensors 2020;20(6589):1–21.
[12] Shaw J, Wang YH, Lin CY. Sound and vibration analysis of a marine diesel engine via reverse engineering. J Mar Sci Technol 2018;26(5):703–11.
[13] Lee TK, Joo WH, Bae JG. Exhaust noise control of marine diesel engine using hybrid silencer. Transac Korean Soc Noise Vibr Eng 2009;19(7):679–84.
[14] Sunarsih S, Nugroho TF, Navyazka MY. Noise reduction in ship engine room by optimisation of muffler design. Int J Mar Eng Innov Res 2020;5(4):224–33.

[15] Chiu MC, Chang YC, Lan TS, Chen HS. Optimization of circular silencers internally hybridized with multiple reverse chambers using the GA method. J Mar Sci Technol 2022; 30(6):322–39.
[16] Fang J, Zhou Y, Jiao P, Ling Z. Study on pressure loss for a muffler based on CFD and experiment, 2009 international conference on measuring technology and mechatronics automation. 2009.
[17] Chen J, Shi X. CFD numerical simulation of exhaust muffler. In: 2011 seventh international conference on computational intelligence and security; 2011.
[18] Galphade A, Patil AV. Design and analysis of muffler for 800 cc car. Int J Adv Res Eng Sci Technol 2015;2(7):72–6.
[19] Hwang PU. A study on the straight-through mufflers, Master degree. Taiwan University; 2001.