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Numerical Analysis of Silencers Composed of Screw Tube, Expansion Cone, Orifice Plate, and Perforated Tube by Finite Element Method

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As the noise of engines in factories results in hearing damage, it is mandatory to install silencers. Traditional noise abatement practices involve using one silencer for each venting noise source, leading to cost increase issues when multiple intermittent venting noises are present. Thus, the need for a smart system capable of switching the venting duct to a specific silencer becomes crucial. To address this need, a smart duct switching system is proposed, integrating electric valves, microphones, a controller, and a single silencer. To enhance noise reduction, various types of silencers are examined to investigate their performance in noise reduction. A finite element method (FEM) was adopted to simulate and evaluate the degree of noise reduction. The transmission loss (TL) of silencers with screw tubes (silencer A), expansion cones (silencer B), orifice plates (silencer C), and perforated tubes (silencer D) was evaluated by simulation with COMSOL software. The results indicated that screws did not reduce noise effectively even when combined with expansion cones, orifice plates, and perforated tubes. However, expansion cones, orifice plates, and perforated tubes effectively decreased noise, and their performance was higher when used without screws. Among the various devices, perforated tubes reduced noise most significantly.

1. Introduction

The noise of boat diesel engines considerably impacts the hearing health of crews.[(1)] Therefore, it is mandatory to use silencers to reduce this noise.[(2)] However, there may still be low-frequency noise according to plane wave theory. The effect of silencers on high-frequency noise reduction has been researched using various models. Chiu *et al.* analyzed a double-chamber silencer with an extended tube and a side inlet/outlet using both the four-pole matrix

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and boundary element methods,[3] and Fang *et al.* investigated the pressure loss of a silencer using a computational fluid dynamics (CFD) model.[4] Chang *et al.* used the boundary element method to predict the sound transmission loss of a silencer composed of multiple connected tubes.[5] Chen and Shi estimated the efficiency of an exhaust muffler using CFD.[6] Rostafinski investigated sound attenuation in a curved duct using an acoustic model.[7] Fuller and Bies explored the effect of sound transmission loss in ducts with various section areas and shapes.[8,9] Kim and Ih predicted the performance of curved/expansion chambers by a four-pole transfer matrix method.[10] Yeh *et al.* analyzed the transmission loss of a linearly expanded tube,[11] while Chiu presented a one-chamber perforated muffler filled with wool.[12] Later, Chiu demonstrated side-branched silencers that reduced broadband noise.[13,14] On the basis of plane wave theory, Chiu constructed a two-chamber muffler with multiple parallel perforated plug tubes.[15] Chiu and Cheng established multi-diffuser silencers to reduce noise also on the basis of plane wave theory.[16] Lan *et al.* proposed screw mufflers with two inlets and one outlet to address multiple noise sources.[17] However, the default openness of the two duct inlets can result in reverse flow phenomena and noise leakage. To overcome this limitation, the smart duct switching system depicted in Fig. 1 can effectively manage the flow path by controlling an electric valve and a sound sensing sensor (microphone). This system ensures that reverse flow and associated noise leakage are mitigated.

To enhance the noise reduction capability, silencers were developed with screw tubes, expansion cones, orifice plates, and perforated tubes in this study: four screw tubes (silencer A), screw tube + expansion cones (silencer B), screw tube + orifice plates (silencer C), and screw tube + perforated tubes (silencer D) (Fig.2). Because of the intricate structures, the finite element method (FEM) was employed to analyze the acoustical field of the noise. To analyze the complex-shape silencers, FEM simulations were conducted using COMSOL software.

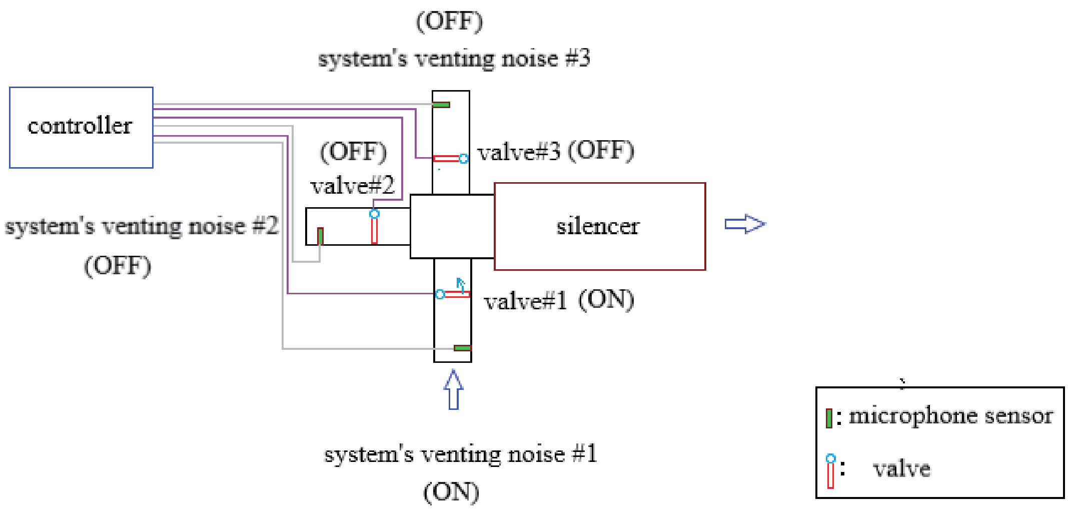
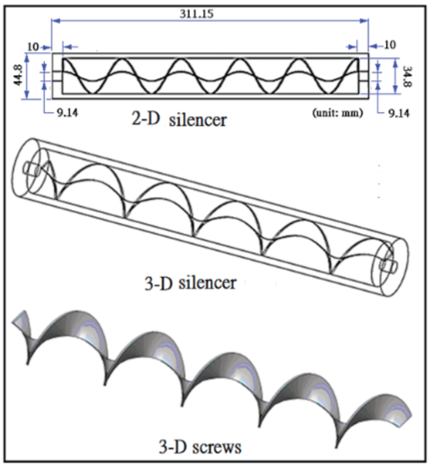
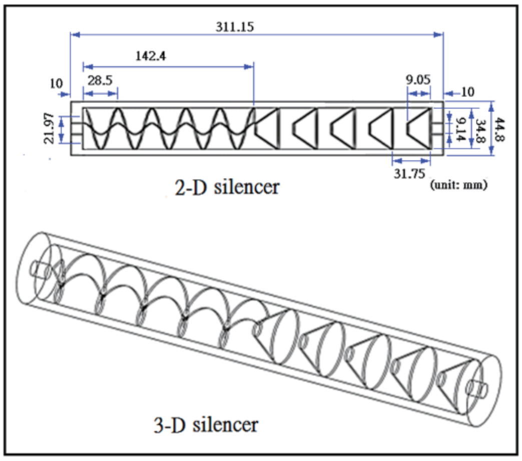


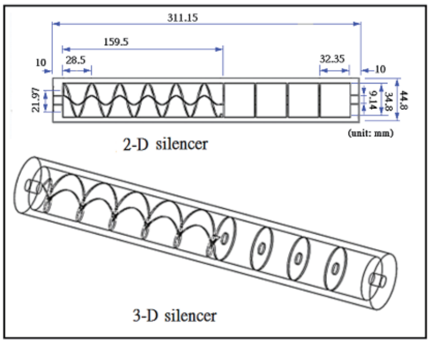
Fig. 1. (Color online) Schematic diagram of a smart duct switching system.



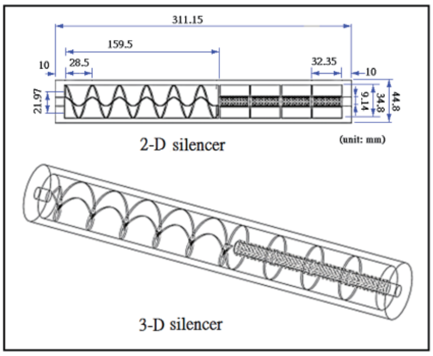
(a)



(b)



(c)



(d)

Fig. 2. (Color online) Four silencers with different parts: (a) silencer A: screw tube, (b) silencer B: screw tube + expansion cone, (c) silencer C: screw tube + orifice plates, and (d) silencer D: screw tube + perforated tube.

2. Methods

The boundary conditions of the screw tubes, orifice plates, and expansion cones is defined as

$$n \cdot \{\frac{1}{\rho_c}(\nabla p_t - q)\} = 0 \,. \tag{1}$$

The boundary condition of the perforated tubes is

$$n \cdot \{\frac{1}{\rho_c}(\nabla p_t - q)\} = -(p_{t1} - p_{t2})\frac{i\omega}{Z_i}, \tag{2}$$

$$Z_i = \rho_c c_c \left[\frac{1}{\rho} \sqrt{\frac{8\mu k}{\rho_c c_c}} \left(1 + \frac{t_p}{d_h} \right) + \theta_f + i \frac{k}{\rho} \left(t_p + \delta_h \right) \right]. \tag{3}$$

The sound wave propagation along the silencer is described as

$$\nabla \cdot -\frac{1}{\rho_c} (\nabla p_t - q) - \frac{k_{eq}^2 p_t}{\rho_c} = Q. \tag{4}$$

The transmission loss (TL) of the silencer in sound is defined as

$$TL = 10 \log \frac{W_{in}}{W_{out}}. \tag{5}$$

To evaluate the performances of the silencers, FEM was used with COMSOL software. Before the evaluation, the COMSOL model was verified on the basis of the simulation results of silencers B and D. Figure 3 shows consistency between the COMSOL and experimental data for a one-chamber silencer, which has an orifice plate at each end.(18) The sound TL of the silencer composed of extended perforated tubes was calculated using the experimental data (Fig. 4).(19)

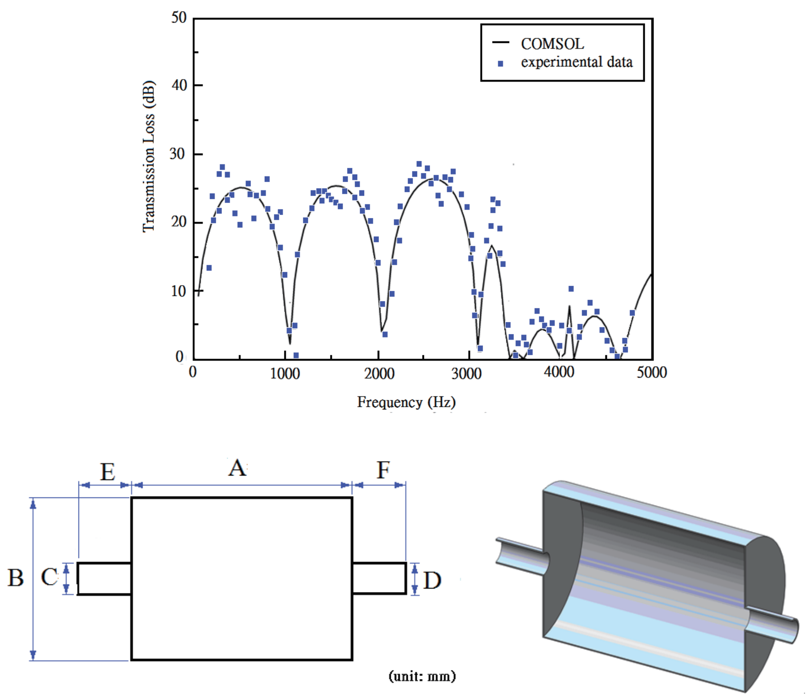
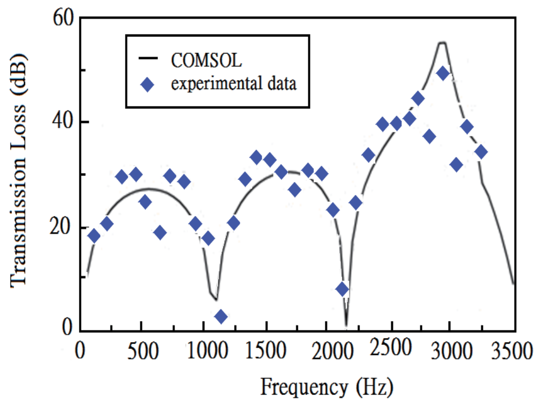


Fig. 3. (Color online) Accuracy of one-chamber silencer with an orifice plate at each end (A = 166.1, B = 123, C = 20.5, D = 20.5, E = 38.7, and F = 38.7).(18)



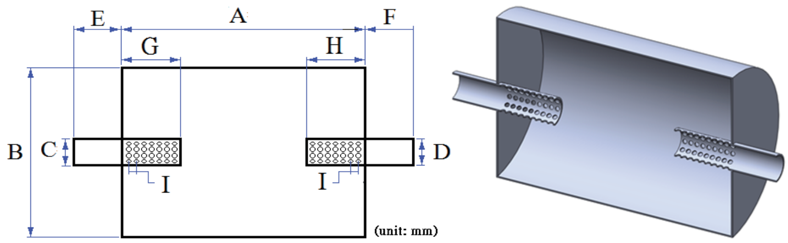


Fig. 4. (Color online) Accuracy check of one-chamber silencer with internally extended perforated tubes (A = 160, B = 118, C = 18, D = 18, E = 30, F = 30, G = 40, H = 40, and I = 3).[19]

3. Results and Discussion

3.1 Results

3.1.1 Silencer A

Silencer A was installed with a screw tube. To examine the acoustical mechanism of silencer A, the pitch of the screws was adjusted to be uniform or nonuniform. With a fixed silencer length, the effect of the pitch on TL was assessed. First, three screw pitches (5, 12, and 15 screws; Fig. 5) were uniformly adjusted. The TL values of the silencers with various screw pitches were calculated (Fig. 6).

Second, two other screw pitch patterns were tested. As shown in Fig. 7, twelve screws with uniform pitches were used to analyze the effect of a nonuniform screw pitch. A screw pitch pattern with 10 screws in three screw groups (6–2–6) was used in the simulation, as shown in Fig. 8. These screw groups had different screw pitches. TL was evaluated and the results of this evaluation are plotted in Fig. 9. Another screw pitch pattern with 14 screws in three screw groups was simulated (Fig. 10). The result for 14 screws in three screw groups of (2–6–2) was compared with that for 12 screws (Fig. 11).

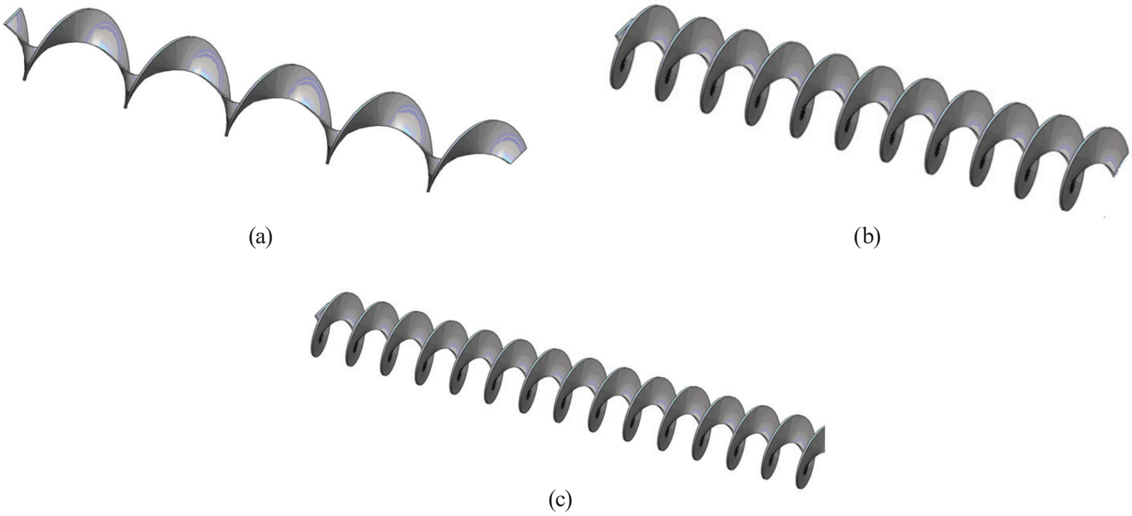


Fig. 5. (Color online) Various numbers of screws with different pitches: (a) 5, (b) 12, and (c) 15 screws.

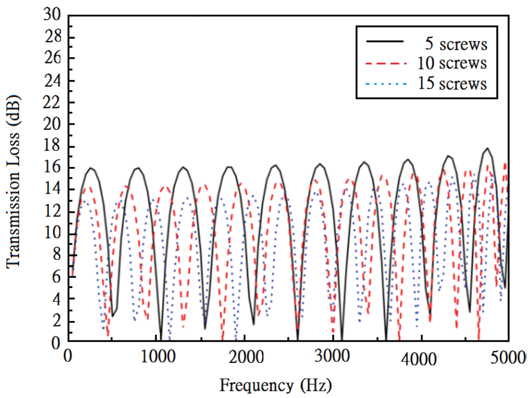


Fig. 6. (Color online) TL values of silencers with various numbers of screws at different pitches.

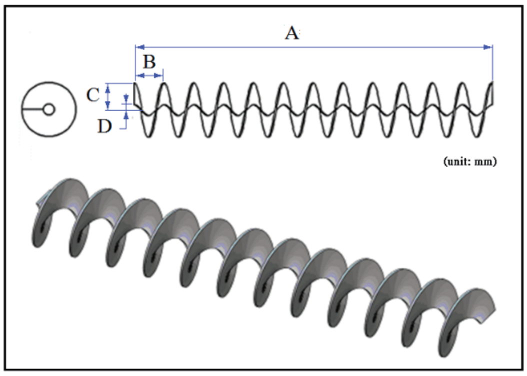


Fig. 7. (Color online) Screws with uniform pitch.

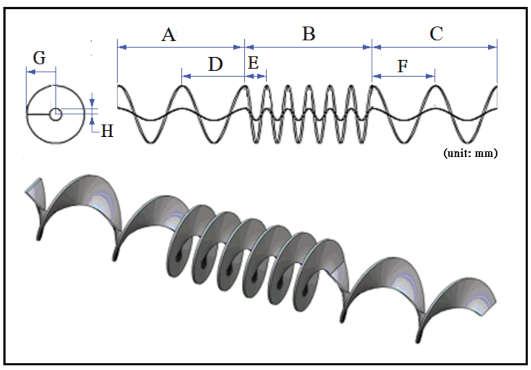


Fig. 8. (Color online) Screw tube with screw pattern of (2–6–2) and screw pitch (A = 96.63, B = 96.63, C = 96.63, D = 48.32, E = 6.1, F = 48.32, G = 21.97, and H = 4.57).

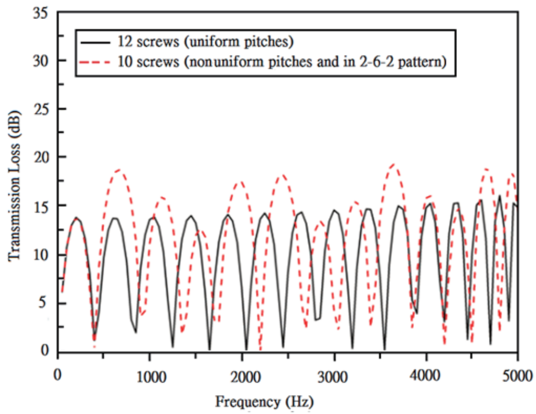


Fig. 9. (Color online) TL values of silencers with different numbers of screws and pitches.

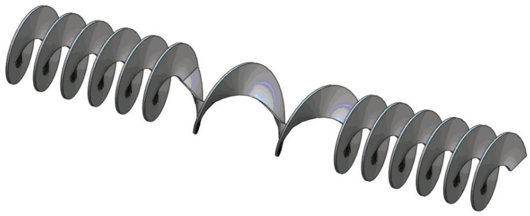


Fig. 10. (Color online) Screw tube with screw pattern of (6–2–6).

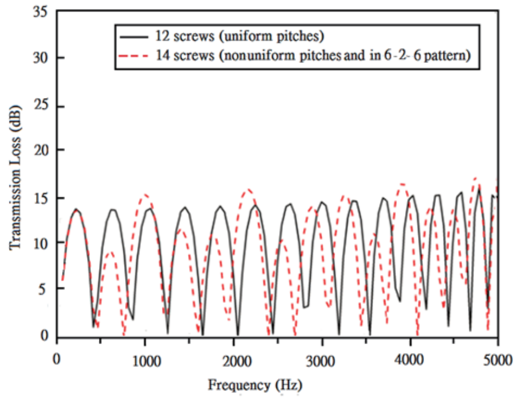


Fig. 11. (Color online) TL values of silencers with different numbers of screws and pitches.

A silencer with the screw tube having different pitches in the pattern of 2–4–6 is depicted in Fig. 12. The acoustical performance was simulated and compared with that of the silencer with 12 screws in a uniform pitch (Fig. 13). As the diameter of the screw tube affects the silencer's acoustical performance, the effect of the adjustment of screw diameter (d_c) has been explored (Fig. 14). TL values of silencers with different d_c values are illustrated in Fig. 15.

3.1.2 Silencer B

Silencer B comprised a screw tube and expansion cones, as shown in Fig. 16. Because the number of screws and the number of expansion cones affect the acoustical performance, they were adjusted as follows: case 1: number of screws = 0, number of cones = 10; case 2: number of screws = 5, number of cones = 5; case 3: number of screws = 10, number of cones = 0. TL was calculated and the results of this calculation are plotted in Fig. 17. The TL values of the silencers in case 4 (number of screws = 5, number of cones = 5), case 5 (number of screws = 3, number of cones = 7), and case 6 (number of screws = 7, number of cones = 3) are shown in Fig. 18.

3.1.3 Silencer C

Silencer C comprised a screw tube and orifice plates, as shown in Fig. 19. The numbers of screws and orifice plates affect the acoustical performance. Thus, the numbers of screws and orifice plates were adjusted as case 7: screws = 0, orifices = 8; case 8: screws = 5, orifices = 4; and case 9: screws=10, orifices = 0, and TL was measured (Fig. 20). TL values in case 10 (screws = 5, orifices = 4), case 11 (screws = 3, orifices = 6), and case 12 (screws = 7, orifices = 2) are shown in Fig. 21.

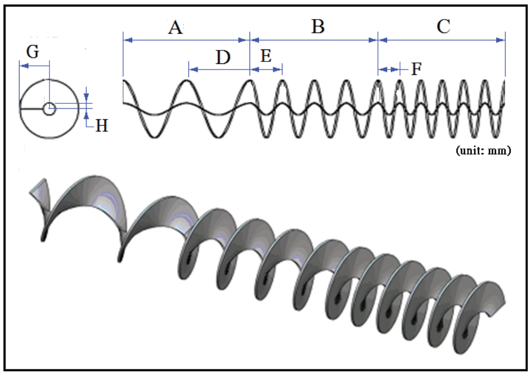


Fig. 12. (Color online) Screws in three pitches of (2–4–6) (A = 96.63, B = 96.63, C = 96.63, D = 48.32, E = 24.16, F = 6.11, G = 21.97, and H = 4.57).

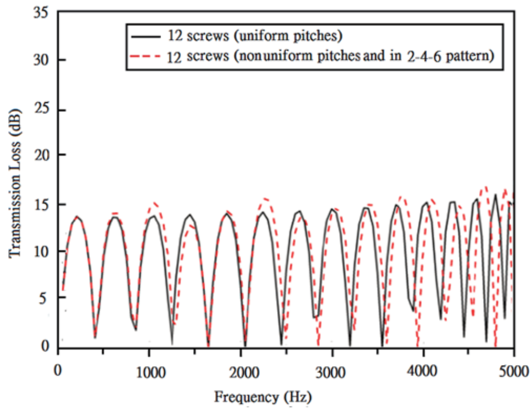


Fig. 13. (Color online) TL values of silencers with different numbers of screws and pitches (2–4–6).

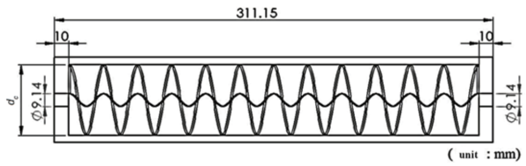


Fig. 14. Adjustment of diameter (d_c) of screw tube with uniform pitch.

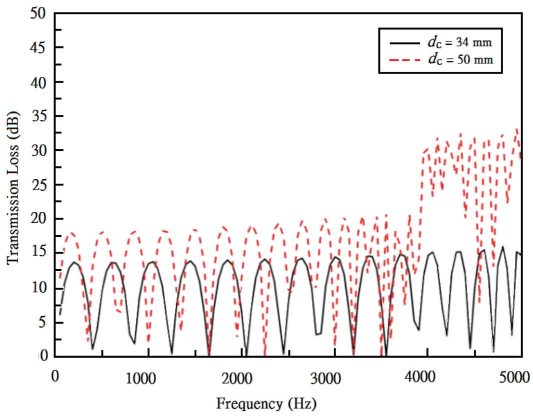


Fig. 15. (Color online) TL values of silencers with different d_c values.

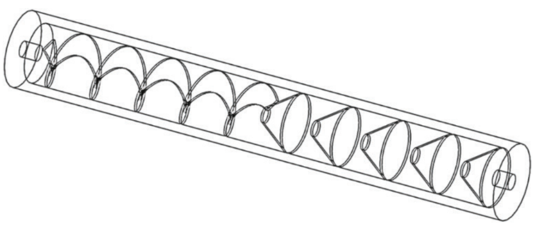


Fig. 16. Silencer B with screw tube and expansion cones.

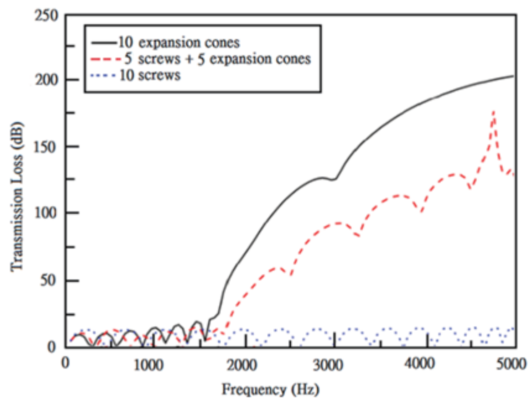


Fig. 17. (Color online) TL values of silencers with different numbers of screws and expansion cones (case 1: black line; case 2: red line; case 3: blue line).

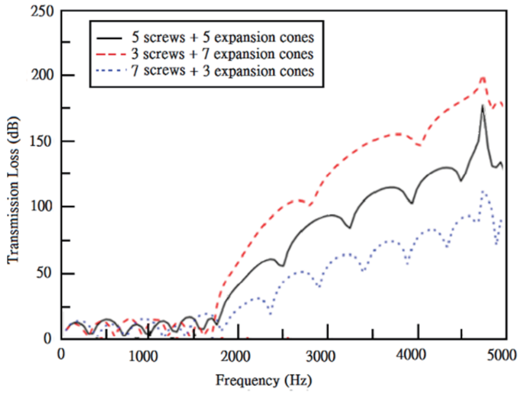


Fig. 18. (Color online) TL values of silencers with different numbers of screws and expansion cones (case 4: black line; case 5: red line; case 6: blue line).

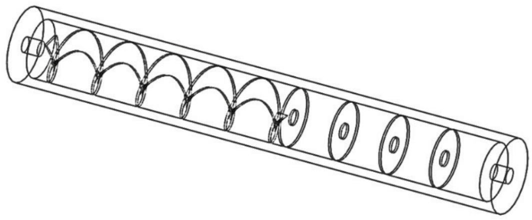


Fig. 19. Silencer C with screw tube and orifice plates.

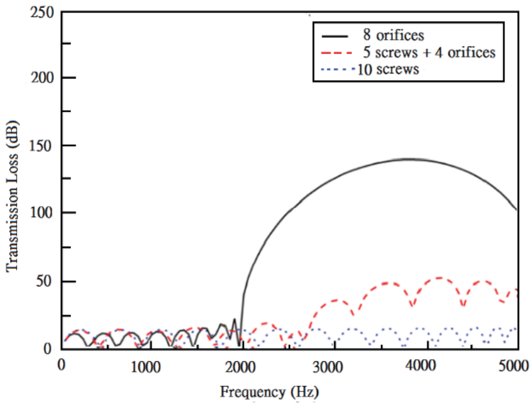


Fig. 20. (Color online) TL values of silencers with different numbers of screws and orifice plates (case 7: black line; case 8: red line; case 9: blue line).

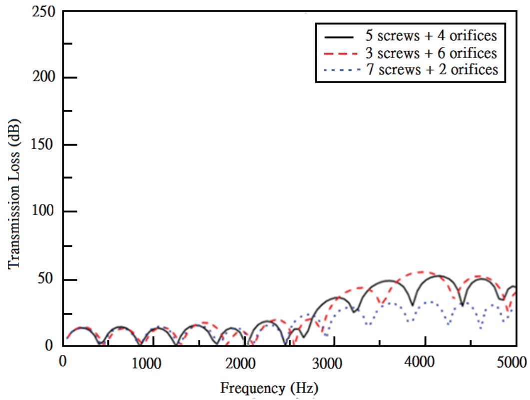


Fig. 21. (Color online) TL values of silencers with different numbers of screws and orifice plates (case 10: black line; case 11: red line; case 12: blue line).

3.1.4 Silencer D

Silencer D comprised a screw tube and perforated tubes, as shown in Fig. 22. TL was measured in three cases (case 13: screws = 0, perforated tubes = 8; case 14: screws = 5, perforated tubes = 4; case 15: screws = 10, perforated tubes = 0), and the obtained results are shown in Fig. 23. TL values in case 16 (screws = 5, perforated tubes = 4), case 17 (screws = 3, perforated tubes = 6), and case 18 (screws = 8, perforated tubes = 2) are shown in Fig. 24.

3.2 Discussion

Traditional noise abatement methods typically involve using one silencer to address each venting noise source, leading to increased costs when multiple intermittent venting noises are present. In such scenarios, the importance of a smart system capable of switching the venting

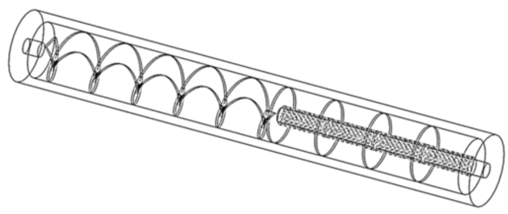


Fig. 22. Silencer D with screw tube and perforated tubes.

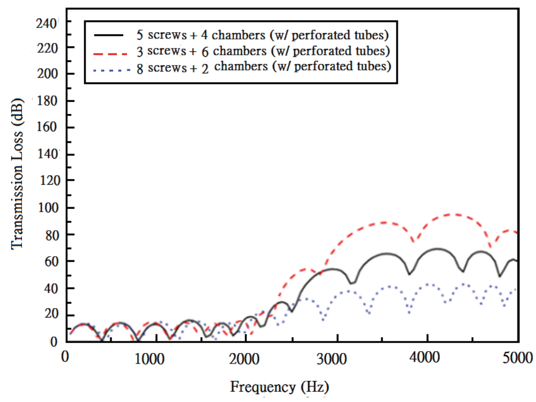


Fig. 23. (Color online) TL values of silencers with different numbers of screws and perforated tubes (case 13: black line; case 14: red line; case 15: blue line).

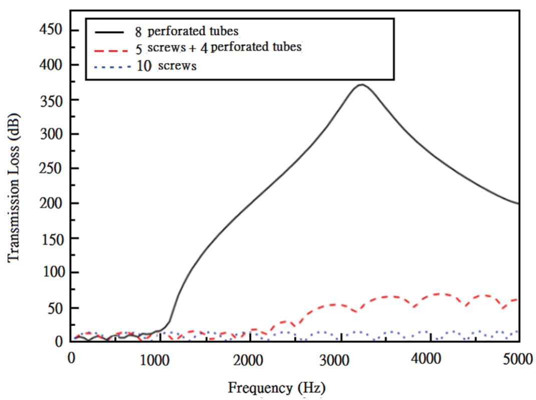


Fig. 24. (Color online) TL values of silencers with different numbers of screws and perforated tubes (case 16: black line; case 17: red line; case 18: blue line).

duct to a designated silencer becomes evident. To achieve this goal of low costs in silencers, we propose the smart duct switching system depicted in Fig. 1, which utilizes electric valves, microphones, a controller, and a single silencer. In this system, each microphone (i) detects elevated noise levels when its corresponding venting noise occurs and relays this information to the controller. Subsequently, the controller activates the i-th electric valve with a high voltage signal, allowing the venting noise flow to be directed to the silencer for effective noise reduction. To further enhance the silencer's performance, we have investigated various acoustical elements such as screw tubes, expansion cones, orifice plates, and perforated tubes by FEM analysis. The noise reduction performance of silencers with screw tubes, expansion cones, orifice plates, and perforated tubes was simulated in this study. Considering a fixed length of silencers, TL values in the cases of 5, 10, and 15 uniformly pitched screws were measured, and the obtained results are shown in Fig. 6. TL decreased with the number of screws. The TL values in the cases of uniform and nonuniform pitches (2–6–2 and 6–2–6) showed that nonuniform pitches showed a greater reduction of noise (increased TL) but the pattern of (2–6–2) reduced noise more considerably than that of (6–2–6). The pitch pattern of (2–4–6) did not decrease the noise significantly. A silencer with a large diameter of 50 mm showed a more effective noise reduction than that with a diameter of 30 mm. It was found that changes in the number of screws and the screw pattern did not markedly affect noise reduction, but the diameter of the silencer had a more significant effect on the performance. The use of expansion cones allowed for greater noise reduction. When using expansion cones alone in the silencer, the noise reduction was greater than when using them with screws. Orifice plates and perforated tubes also had the same effect as expansion cones, indicating that the use of orifice plates, perforated tubes, and expansion cones without screws reduced noise far more effectively. The results showed that perforated tubes were the most effective in reducing noise. It was also found that noise was effectively reduced by orifice plates, perforated tubes, and expansion cones with a small number of screws. Again, the best noise reduction was observed without screws for orifice plates, perforated tubes, and expansion cones.

4. Conclusions

In traditional noise abatement practices, a single silencer is typically employed to mitigate the noise from one venting source. However, when dealing with multiple intermittent venting sources, this approach can result in increased costs. In contrast, Chiu and Cheng[16] recently employed a single silencer with two open duct inlets to address venting noise. Nevertheless, the constant openness of the two duct inlets may cause a reverse flow phenomenon, leading to noise leakage. To mitigate this issue, a smart duct switching system has been proposed. This system utilizes an electric valve and a sound sensor (microphone) to control the flow path effectively. By implementing this system, the adverse effects of reverse flow and noise leakage can be effectively avoided. To advance the noise reduction of the silencer, we simulated the performance of silencers installed with screw tubes, expansion cones, orifice plates, and perforated tubes. Without expansion cones, orifice plates, or perforated tubes, noise was not decreased effectively regardless of the number of screws. The pitch pattern did not affect the performance of the silencer except for the pitch pattern of (2–6–2) with 10 screws, which decreased noise significantly. Expansion cones, orifice plates, and perforated tubes enhanced the noise reduction of the silencer compared with screws. Without screws, they effectively decreased noise considerably. The results show that the silencer should be equipped with expansion cones, orifice plates, and perforated tubes; screws are not recommended for effective noise reduction. Among expansion cones, orifice plates, and perforated tubes, perforated tubes showed the highest noise reduction. Consequently, we have introduced a novel approach to managing multiple intermittent venting flows through the implementation of a smart duct switching system. Furthermore, we offer a comprehensive guideline for silencer design, which can greatly benefit readers interested in noise abatement work.

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