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A STUDY OF THE EFFECT OF PERFORATED MUFFLER OF VEHICLE ON NOISE CHARACTERISTICS AT THE SPECIFIC FREQUENCY

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Abstract. *A perforated pipe is an essential component to reduce noise in muffler systems. Using the three-dimensional finite element model, the frequency ranges where the transmission loss occurred due to the perforation on the pipe were investigated. The model was validated by the comparison of the results with experimental data. The simulation results show that the perforation affects TL mostly at 400-800 Hz, and 1200-1700 Hz.*
Keywords: Muffler, Transmission loss, Perforated pipe, Frequency, Noise

1. **Introduction.** The mufflers are often used to reduce noise generated by the exhaust system. Mufflers are mounted into various types of vehicles in order to attenuate the noise. And, the vehicles have their own noise characteristics (NC). Therefore, the muffler for each vehicle should be designed considering the NC. One of the significant factors of the muffler affecting the NC is the perforated pipe. There have been many studies about the effects of the perforated pipe on the NC [1-5]. However, there has been little study to analyze the NC related to the specific input frequencies in the muffler. In this study, therefore, we will study the specific frequencies affected by the perforated pipe in the muffler using a three-dimensional finite element (FE) model of the muffler.

2. **Method.** In this study, we focused on the responses of the muffler excluding those of other components of the vehicle such as an engine, tire, and transmission. For the analysis of the muffler response, we compared the simulation results from the FE model with experiment data.

Figure 1 shows the geometry of the muffler used in this study. Its type is the muffler whose inlet and outlet are not in parallel [6,7]. The inside of the muffler was divided into three different expansion chambers. In this study, the chambers from the inlet to the outlet were named as ①, ②, and ③ chambers in order (See Figure 1(a)). In addition, the inlet and outlet were also named as ⓐ and ⓑ, respectively. The length of the ① and ③ chambers were 177.8 mm, while that of the ② chamber was 127 mm. The perforated pipes in the muffler connect the ⓐ-③, ③-①, and ①-ⓑ chambers, respectively, and the perforation rate of all the pipes was 21.6%. If the perforation of the pipe is ignored, the air in the muffler flows from the inlet to the outlet along the pipes through ③ and ① chambers in order. Due to the perforation, however, the air in the ② chamber and pipes can communicate each other. The number of the perforation in a pipe was 540, and the diameter of the pipe was 3 mm.

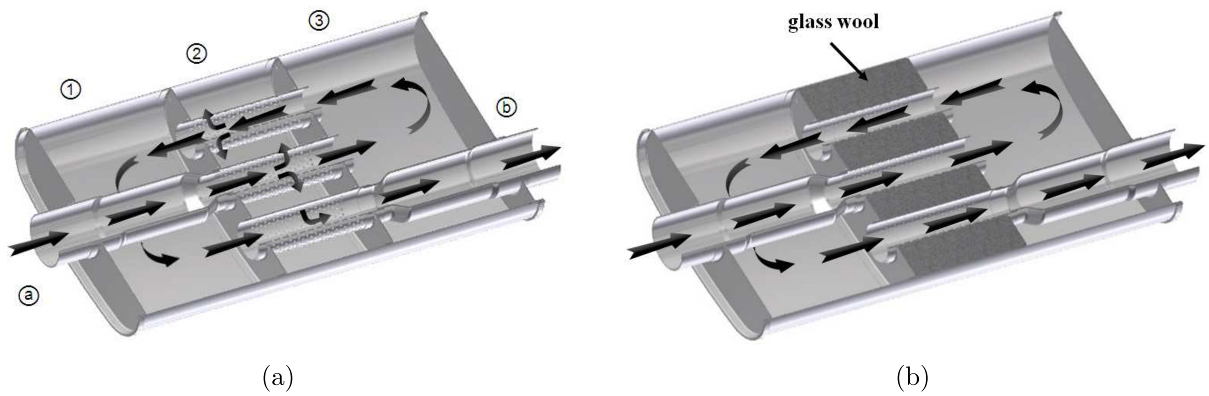

FIGURE 1. Geometry of the used muffler when (a) there is no glass wool in the center chamber, and (b) there exists glass wool in the center chamber. The chambers of the muffler were named as the ①, ②, and ③, respectively. In addition, the inlet and the outlet are indicated by ⓐ and ⓑ, respectively. The arrows in the chambers represent the flow of the air at each case.

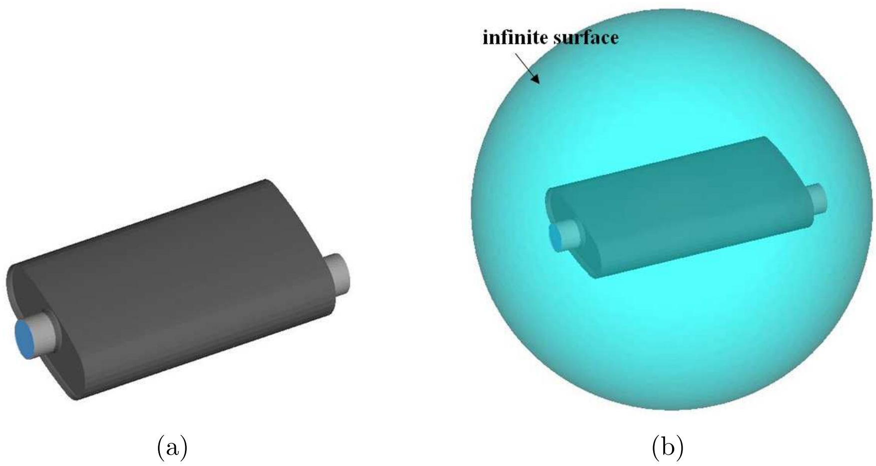

FIGURE 2. (a) A 3D FE model of the muffler. (b) The cyan-transparent surface represents the infinite fluid element.

2.1. **Development of the 3D FE model.** Based on the obtained geometry, a three-dimensional FE model was developed for the analysis. For the pre-process, a commercial software, HYPERMESH (Altair Engineering, Troy, MI, USA), was used. 1,202,000 tetrahedron fluid elements including 384,000 porous elements were generated for the acoustic components in the muffler whereas 243,000 tetrahedron solid elements were used for the solid structure of the muffler. Specifically, the infinite fluid surface was defined in the model to prevent the sound wave reflection (See Figure 2(b)). The infinite fluid surface was represented by a two-dimensional element. Figure 2 shows the developed FE model of the muffler.

The mechanical properties of the components of the muffler including glass wool were determined by the reference values at 10°C and 1 atm. The details are described at Table 1.

2.2. **Transmission loss.** In the simulation, the noise reduction through the muffler was described by the transmission loss (TL). The TL was defined as the following:

$$\mathrm{TL} = 10\log_{10}\left[\int \frac{P_o^2 dt}{P_i^2 dy}\right] = 20\log_{10}\left[\int \frac{P_o dt}{P_i dy}\right] + 10\log_{10}\left[\int \frac{S_o dt}{S_i dy}\right] \tag{1}$$

where P_o, P_i, S_o, and S_i represent transmission wave pressure (Pa), incident wave pressure (Pa), outlet area (mm^2), and inlet area (mm^2), respectively.

2.3. **Simulation.** For the FE analysis, a commercial software, ACTRAN (Free Field Technologies, BE), was used to solve the linear Helmholtz equation. Specifically, the effect of the glass wool was simulated by using porous material. Details of the glass wool are summarized in Table 2.

Table 1. Air and steel material property for analysis. The material properties for fluid are density and sound speed, whereas those for solid are Young's modulus, Poisson ratio, and density.

	air	steel
Fluid Density [kg/m^3]	1.246	–
Sound Speed [m/s]	373	–
Young Modulus [GPa]	–	210
Poisson Ratio	–	0.3
Solid Density [kg/m^3]	–	7,890

Table 2. Mechanical properties of the used porous material

	Glass wool
Fluid Resistivity [Pa s/m^2]	15000
Viscous Length [μm]	35.0
Thermal Length [μm]	108.0
Young Modulus [kPa]	1400
Solid Density [kg/m^3]	132.14
Poisson Ratio	0.01
Tortuosity	1.01
Porosity	0.95

The glass wool formulation involves both the fluid and the skeleton of the porous material. The basic equations for the fluid and solid phase are as the following:

$$\Omega^2 \left[\widetilde{\rho}_{ij}^{22}\right]^{-1} \partial_{ij} P + \omega^2 \frac{\Omega^2}{\widetilde{R}} P \cdot \omega^2 \widetilde{\gamma}_{ij} \partial_i u_j = 0 \tag{2}$$

$$\partial_j \widetilde{\sigma}_{ij}^S + \omega^2 \widetilde{\rho}_{ij} u_j + \widetilde{\gamma}_{ij} \partial_j P = 0 \tag{3}$$

$$\hat{\sigma}_{ij}^S = \widetilde{C}_{ijkl} \epsilon_{kl} - Q(\alpha - \Omega)^2 \partial_k u_k \delta_{ij} - (\alpha - \Omega) P \delta_{ij} \tag{4}$$

where Ω is the porosity, $\widetilde{\rho}$ is an adapted density tensor, P is the acoustic pressure, ω is the angular frequency, R is the resistivity of the media, $\widetilde{\gamma}$ is the skeleton's deformation to the pore pressure, μ is the displacement of the skeleton, $\hat{\sigma}_{ij}^S$ is the stress tensor, Q is the dilatation coupling coefficient, and $\widetilde{C}$ is the fourth order solid frame Hooke's tensor.

2.4. **Experiments.** A prototype of the muffler based on the above geometry was made and tested in an anechoic room. A white noise was emitted at the inlet of the muffler, and the acoustic pressure was measured at both inlet and outlet of the muffler using the micro phone. Figures 3 and 4 show the detailed set-up for the experiment. Then, the sound pressure difference at both ends was calculated to quantify the noise reduction.

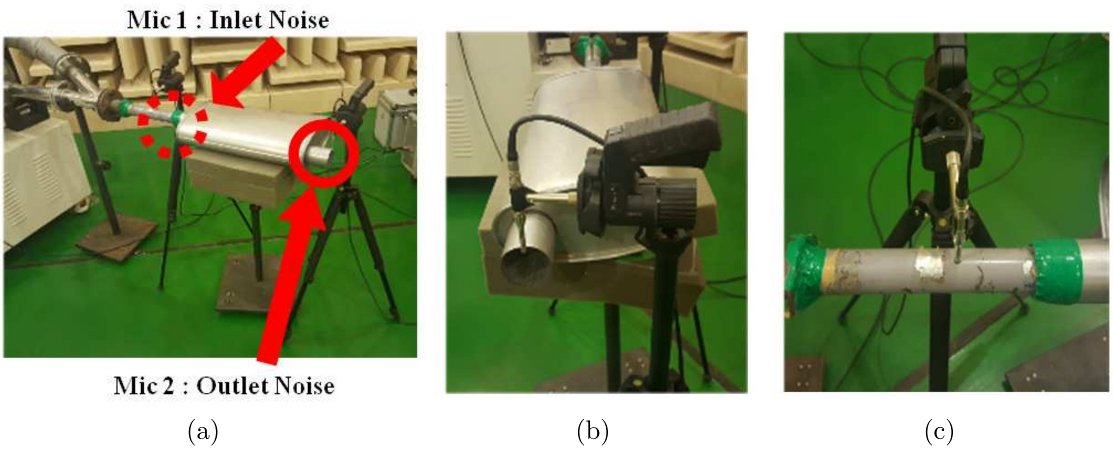

FIGURE 3. (a) The placed muffler on the fixed table. Setting up for the measurement of the sound pressure from (b) the outlet and (c) the inlet.

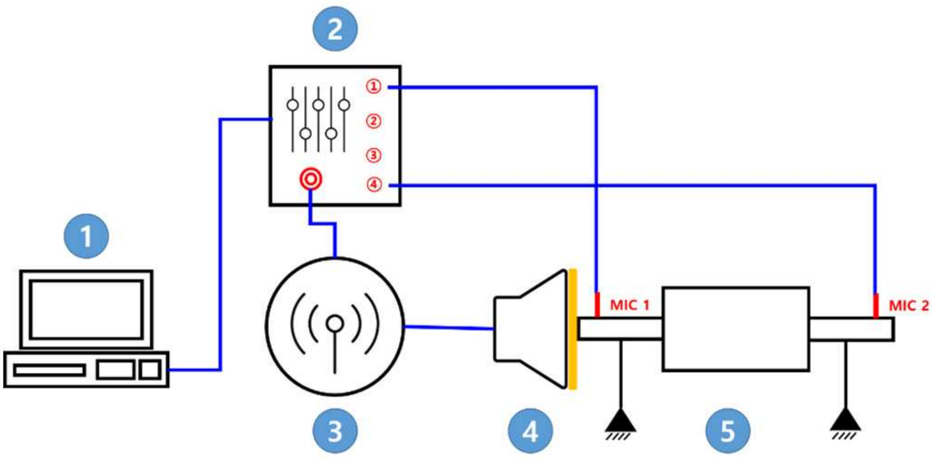

FIGURE 4. Lay-out of the experiment system. ①: Test. Lab (Noise Analyzer), ②: Signal Generator, ③: AMP, ④: Speaker, ⑤: Muffler.

3. Results.

3.1. Model verification. Figure 5 shows the comparison of the TL of the experiment and simulation. The TLs of the experiment and simulation were described by a dash and a solid line, respectively. It should be noted that, in both cases, the glass wool was inserted into the ② chamber.

From 300 Hz to 600 Hz, there are about 20-30 dB differences between two cases. However, except those frequencies, the results of the experiment and simulation were reasonably consistent with 10 dB differences.

3.2. Effects of perforated pipes. Figure 6 shows the comparison of the TL of the two different simulations. The solid line is obtained by simulation with normal muffler model without glass wool in the ② chamber. On the other hand, the dotted line is determined by simulation using the same muffler with the above case, but including the glass wool in the ② chamber. As shown in Figure 6, the TL at the formercase was 10 to 20 dB lower than that of the lattercase between 400 to 800 Hz, and 1200 to 1700 Hz. At those frequencies, the noise attenuation was better in the case using glass wool since the glass wool absorbed the sound leaked out from the perforated hole.

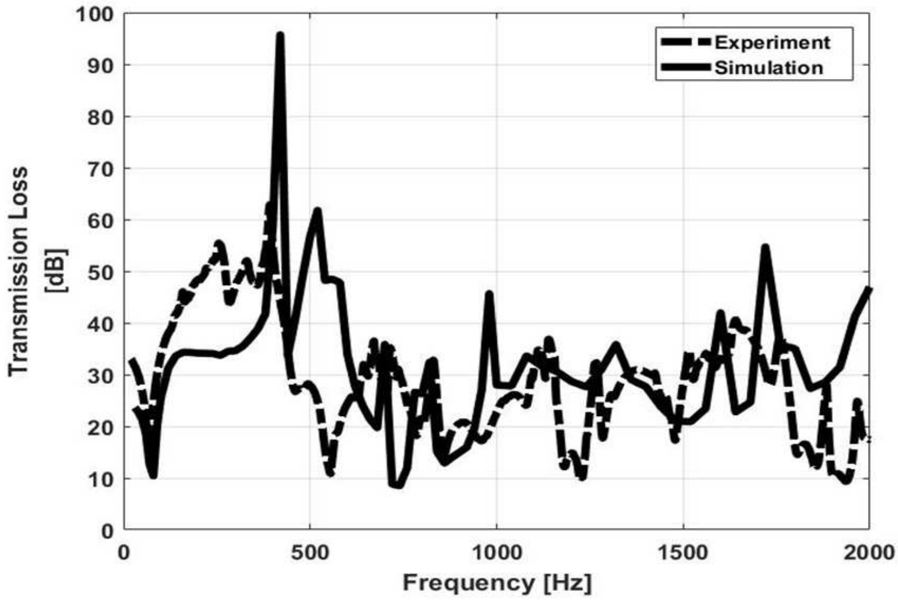

Figure 5. Comparison of experiment and simulation results. Transmission loss of both cases are reasonably similar to each other from 600 Hz to 2 kHz.

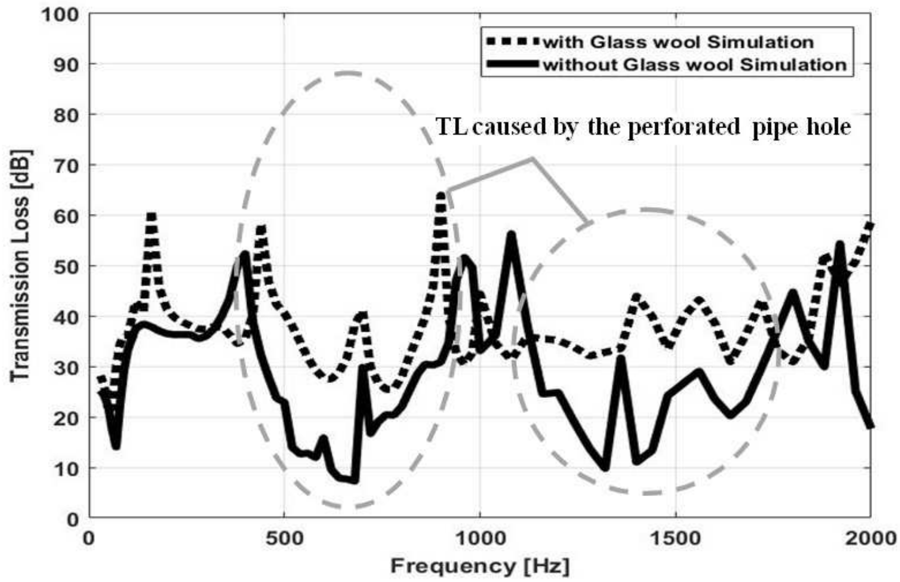

Figure 6. Comparison of transmission loss of two different cases, which are (1) with glass wool (dotted line), and (2) without glass wool (solid line) in the ② chamber. Between 400-800 Hz, and 1200-1700 Hz, without glass wool case shows lower value about 10-20 dB than with glass wool case.

4. **Discussion.** According to Sasikumar and Kumar [8], the shape and rate of the pipe perforation affect decreasing of the average TL. However, there was no discussion about the frequency range affected by the shape and rate of the pipe perforation. As shown in Figure 6, TLs at 400 to 800 Hz, and 1200 to 1700 Hz were affected by the existence of glass wool in ② chamber, which means that the fluid flow from the hole of the perforated pipe into the ② chamber was absorbed by the glass wool. In other words, the fluid flow through the perforation at the ② chamber is dominant at 400 to 800 Hz, and 1200 to 1700 Hz. Therefore, if drivers want to hear noise or sound at those frequencies, we can satisfy it by modifying the geometry of the perforation. However, this study has the following

caveats: the frequency ranges where TL can be affected by not only the perforation but also the other inside structure of the muffler. In other words, the current model has the fixed shape except the perforation shape and rate. Hence, if the geometry of the muffler is changed, we have to redo above the simulation to obtain the specific frequency band.

5. **Conclusions.** We investigated the frequency range where TL was affected due to the perforation in the pipe using the 3D FE model. The model was validated by the comparison of the response with experimental results. Furthermore, according to the simulation results, the perforations in the pipe affect the TL mostly at 400 to 800 Hz, and 1200 to 1700 Hz frequency ranges in a given muffler. In the future, new mufflers will be designed considering modification of the shape and rate of the perforation in the other muffler models.

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