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Sound Transmission Loss Prediction of a Wiring Grommet by Using the FEM

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ABSTRACT

This paper focuses on predicting the sound transmission loss (STL) of a wiring grommet using the finite element method (FEM). The wiring grommet is used to reduce the noise transmitted through a wiring hole and is combined with a wiring harness passing through the wiring grommet. To predict the STL of the wiring grommet combined with the wiring harness, an FEM analysis was performed in the following two steps. In the first step, appropriate assembly conditions were applied to account for the change in the dynamic characteristics of the wiring grommet due to its coupling with the wiring harness. The outer diameter of the wiring harness is slightly greater than the internal diameter of the wiring grommet, resulting in a contact pressure on both sides. Because of the change in the dynamic characteristics of the wiring grommet due to such a contact pressure, the coupling conditions were considered. In the second step, an acoustic analysis was performed considering the viscoelastic characteristics of the wiring grommets with frequency dependent storage and loss modulus. Finally, the effect of the wiring harness on the STL of the wiring grommet was examined, and the validity of the modeling was verified by comparing with the STL measurement results.

Keywords: Sound Transmission Loss, Wiring Grommet, Finite Element Method
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

Consumers today expect quieter vehicles. Thus, it has become an important issue for the automobile industry to minimize the noise transmitted into the vehicle interior from external and internal noise sources.

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To reduce the noise coming from exterior noise sources, there has been a growing interest in vehicle sealing systems. More specifically, as door seals play an important role in mitigating vehicle interior noise at mid and high frequencies, many studies have been conducted on door seals using numerical methods, such as the finite element method (FEM)[1-3] and statistical energy analysis (SEA)[4], for predicting the sound transmission loss (STL), which indicates the sound insulation performance.

The wiring grommet is mounted on the wiring hole inside the dash panel and is used to minimize the transmitted noise radiated from the engine, which is considered the main internal noise source inside the vehicle. As wiring holes are vulnerable to noise, it is important to evaluate or predict the sound insulation performance of wiring grommets. In recent years, FEM has been employed to predict the insertion loss (IL) of wiring grommets[5]. However, studies on the STL prediction of wiring grommets are lacking.

To predict the STL of a wiring grommet, the following two steps were implemented in this study. In the first step, the change in the dynamic characteristics due to the assembly of the grommet and the wiring harness is considered. The outer diameter of the wiring harness is slightly greater than the inner diameter of the grommet to prevent sound from transmitting through the contact surface. Because of this contact pressure, the grommet and wiring harness have radial displacements and are brought into contact with each other. To accurately model the contact conditions, the Young's modulus of the wiring grommet was measured, and the equivalent modulus of the wiring harness was then calculated[6]. In the second step, an acoustic analysis was performed considering the complex Young's modulus of the ethylene propylene diene monomer (EPDM) rubber, comprising the storage modulus G_s and the loss modulus G_l, which vary with the frequency. The storage modulus is a measure of the elastic behavior of the rubber, whereas the loss modulus is a measure of the viscous behavior. Finally, the effect of the wiring harness on the STL of the wiring grommet was examined, and the validity of the modeling was verified by comparing with the STL measurement results.

2. MODELING PROCESS FOR STRUCTURAL ANALYSIS

2.1 Contact Analysis

The model used in the FEM consists of a wiring grommet and a wiring harness, as shown in Figure 1. To model the coupling condition due to the normal force between the two contact surfaces, a contact analysis was performed using the commercial software NX12.0.

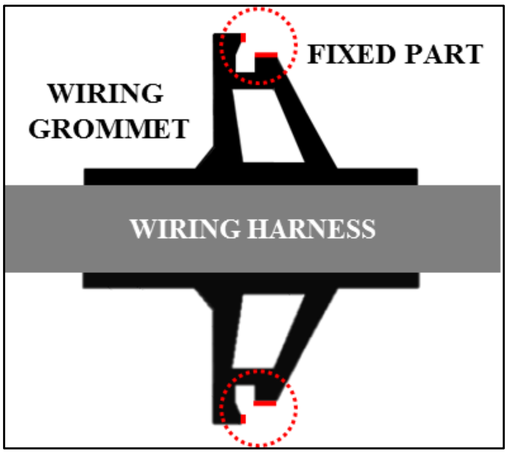


Fig. 1 − Schematic of assembly of wiring grommet and wiring harness.

In the contact analysis, a contact element between the two adjacent faces is initially created, as shown in Figure 2. Subsequently, the state of the contact element changes as the inner and outer loops progress. The inner loop adjusts the forces and penetrations and the outer loop updates the state of the contact element. If the calculated convergence tolerance and the number of contact elements changes are less than the criteria, the contact analysis is said to be complete[7]. The stiffness of the contact element generated through the above process can be calculated using Equation 1.

$$K = e\,E\,dA \tag{1}$$

where e is the penalty factor in the normal or transverse directions, calculated using the geometrical characteristics, E is the elastic modulus of the softer material in each contact pair, and dA is the area associated with the contact point. As the deformation of the grommet due to the weight of the wiring harness is small with no change in the contact surface, a linear contact analysis was performed.

2.2 Modeling of Wiring Harness

Generally, the modeling of the wiring harness is complicated because the stiffness of the wiring harness changes depending on the wire material, lay angle, and helix angle wrapped degree. The stiffness of the wiring harness is significantly higher than that of the rubber constituting the grommet. Therefore, it does not affect the stiffness of the contact element.

In this study, the equivalent Young's modulus of the wiring harness was calculated using the mechanical properties of copper, which the conductor cores are made of, and cross-linked polyethylene (CLP), which is used for insulating the interior and exterior wires. The Young's moduli of copper and CLP are 110 and 0.9 GPa, respectively, and the volume fractions are 0.67 and 0.33, respectively. Thus, the equivalent Young's modulus is 73.6 GPa[6]. A parametric study was carried out to investigate the effect of the Young's modulus of the wiring harness on the STL of the wiring grommet to examine the need to precisely model the wiring harness.

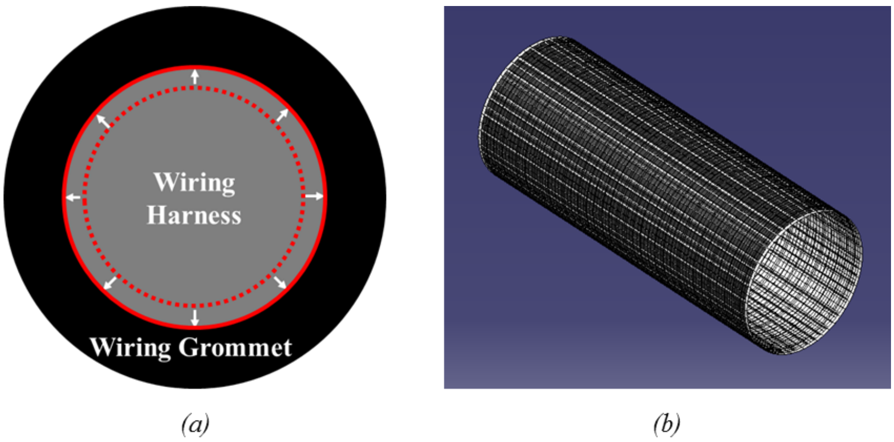


Fig. 2 − (a) Schematic representation of interference-fit; the red dotted portion indicates the inner diameter of the grommet before interference, whereas the red solid portion indicates the inner diameter after interference; (b) Initial creation of contact elements between the two contact surfaces.

3. SOUND TRANSMISSION LOSS MEASUREMENT

The STL is an indicator of the sound insulation performance and is defined in Equation 2. The transmission coefficient τ in Equation 3 is the ratio of the transmitted sound power W_t to the incident sound power W_i.

P_{rms}^2 is the root-mean-square pressure, c is the speed of sound in air, ρ is the air density, $\boldsymbol{S_i}$ and $\boldsymbol{S_t}$ are the wiring grommet surface areas on the reverberant and semi anechoic sides, respectively, and I_t is the transmitted acoustic intensity on the semi-anechoic room side.

$$STL = 10log_{10}\left(\frac{1}{\tau}\right) \quad (2)$$

$$\tau = \frac{W_t}{W_i} \quad (3)$$

$$W_i = \frac{S_i P_{rms}^2}{4\rho c} \quad (4)$$

$$W_t = S_t I_t \quad (5)$$

The STL of the wiring grommet combined with the harness was measured in a semi-anechoic and reverberant room at the Seoul National University, South Korea. The overall procedure followed the guidelines of the ASTM E90 international standard[8].

Because of the small size of the wiring grommet, it is difficult to install it between the semi-anechoic and reverberation room. Therefore, it is assembled in the aperture of a sound barrier fixture, as shown in Figure 3.

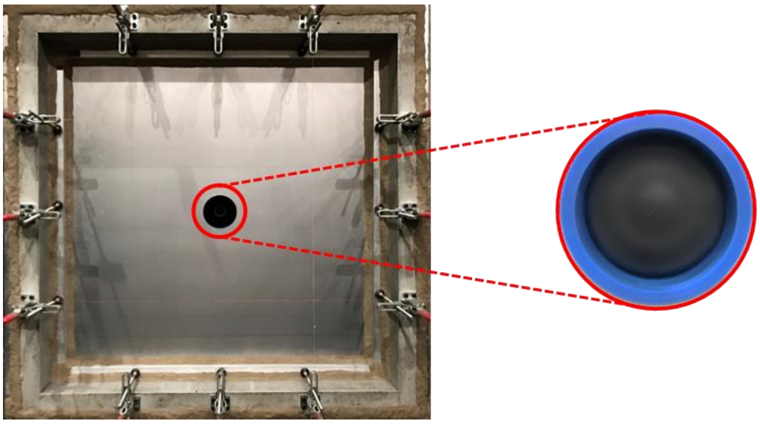


Fig. 3 − Measurement of sound transmission loss of wiring grommet using sound barrier fixture.

The transmission coefficient of the wiring grommet is calculated using Equation 6.

$$\tau_{grommet} = \frac{\tau_{composite} - \tau_{barrier}(S_{barrier}/S_{total})}{(S_{seal}/S_{total})} \quad (6)$$

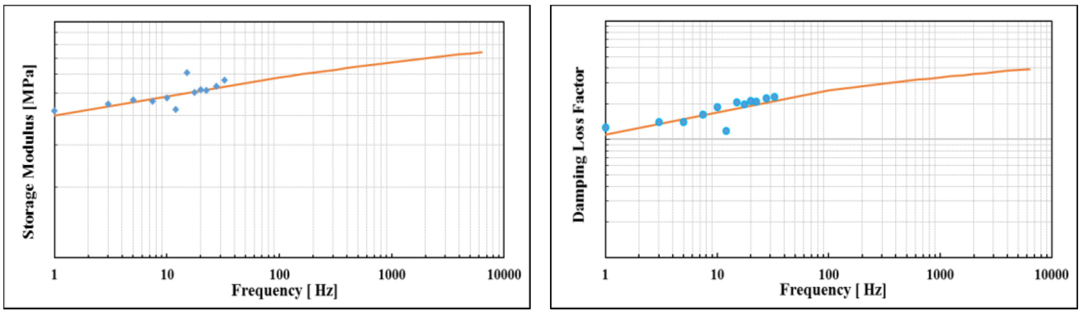
where $\tau_{barrier}$ is the transmission coefficient of the sound barrier before the aperture is created, $\tau_{composite}$ is the transmission coefficient in combination with the sound barrier fixture and the wiring grommet, and S_{total} is the surface area scanned by the intensity probe. The average sound pressure was obtained from the rotating microphone boom in the reverberant room to calculate the incident power, as given in Equation 4, and the transmitted power was measured using an intensity probe installed in the semi-anechoic room. Finally, the STL of the wiring grommet was obtained by calculating its transmission coefficient using Equation 6.

However, it should be noted that the STL of the sound barrier fixture must be higher than that of the wiring grommet for measuring the STL of the wiring grommet. Therefore, the STL of the wiring grommet could be measured in the frequency range above a one-third octave center frequency of 400 Hz.

4. MATERIAL TEST

The grommet was made of EPDM rubber. The dynamic mechanical analyzer (DMA) 8000 (from PerkinElmer) was used to measure the storage and loss modulus with respect to the frequency via a single cantilever mode. Damping loss factor (DLF) which is the ratio of loss modulus to storage modulus was calculated. For the material testing, 3 cm long, thin material samples were used. Preloading conditions were ignored, and a small static and dynamic force was applied to obtain the linear viscoelastic behavior.

Twelve values were measured at a frequency below 50 Hz, and the least-squares method was applied to the measured dataset to estimate the storage modulus and DLF of the EPDM rubber in the frequency range of interest, as shown in Figure 4.



(a) (b)

Fig. 4 − Measured and estimated (a) Storage modulus and (b) Damping loss factor of the EPDM rubber.

5. ACOUSTIC ANALYSIS

5.1 Vibro-Acoustic Model of Wiring Grommet

The commercial software NX 12.0 was used to predict the vibro-acoustic behavior of the wiring grommet. To perform the acoustic analysis up to a one-third octave band center frequency of 6300 Hz, an acoustic mesh was created with a 3 mm size. An automatically matched layer (AML), which is an artificial layer that helps simulate nonreflecting boundary conditions, was applied to the outer surface of the acoustic mesh, and 12 distributed plane waves were used to simulate the diffuse field, as shown in Figure 5.

5.2 Parametric Study

In previous studies, the effects of Young's modulus and DLF on the STL were investigated numerically. Previous studies have found that the DLF mainly affects the

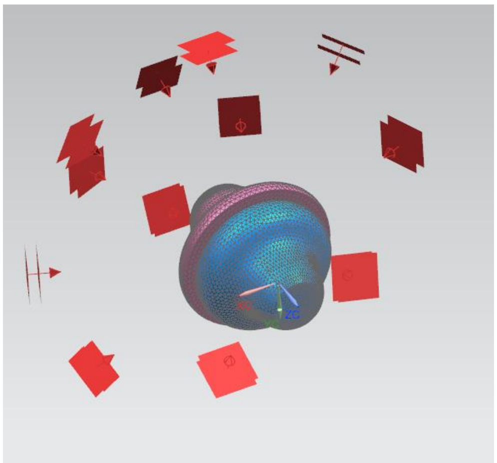


Fig. 5 − FEM model of wiring grommet for vibro-acoustic analysis.

STL in the resonance region and that the Young's modulus significantly influences the value of the resonance frequency and the stiffness-controlled region. In this study, we mainly focused on the effect of the wiring harness on the STL of the wiring grommet.

First, we examined the effect of the wiring harness offset on the STL of the wiring grommet. As it is difficult to accurately determine the offset of the wiring grommet, it is necessary to investigate the effect of the offset on the STL of the wiring grommet. A parametric study was performed for offsets of 0.5, 1, and 2 mm, and the linearity of the EPDM rubber was confirmed based on the contact pressure between the two surfaces.

The offset mainly affects the normal force acting between the two contact surfaces, thus changing the stiffness of the grommet. To include this differential stiffness effect, a dynamic analysis was performed based on a normal mode analysis. The normal mode analysis was performed up to 8000 Hz, and the value corresponding to 10 times the Young's modulus of the EPDM rubber was used for computation speed.

As shown in Figure 6, the effect of the offset on the STL of the wiring grommet is insignificant and is limited to the low-frequency range. This means that the change in the differential stiffness with respect to the change in the offset is not significant. In the subsequent analysis, the offset is set to 1 mm.

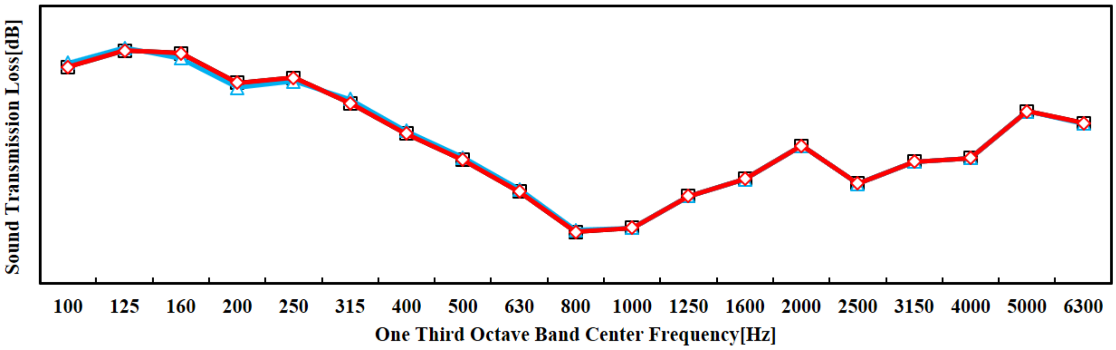


Fig. 6 − STL prediction results of wiring grommet with respect to offsets: 0.5 ( ), 1.0 ( ), and 2.0 mm ( ).

Second, the effect of the wiring harness on the STL of the wiring grommet was investigated. A fluid model was generated for each of the cases where there is wiring grommet only and the wiring harness and the wiring grommet were combined, as shown

Figure 7. In the case of wiring grommet only, the boundary conditions were not applied to the inner diameter of the grommet, and the sound wave was prevented from passing through the inside of the grommet. In both the cases, the measured storage modulus and DLF were used.

Figure 8 shows the calculation result. The STL difference is mainly observed in the low-frequency band, i.e., below 1000 Hz. This is because the contact element reinforces the stiffness of the wiring grommet. It is noteworthy that the STL increases by approximately 9 dB because of the wiring harness at a one-third octave band center frequency of 1000 Hz.

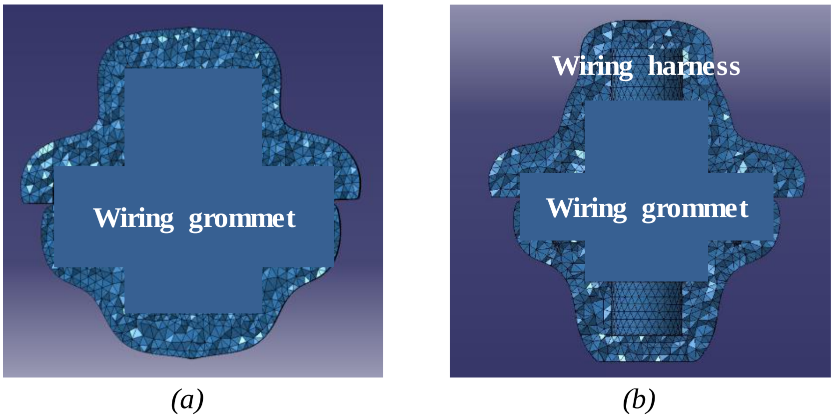


Fig. 7 – Fluid mesh for (a) Wiring grommet only and (b) Assembly of wiring grommet and wiring harness.

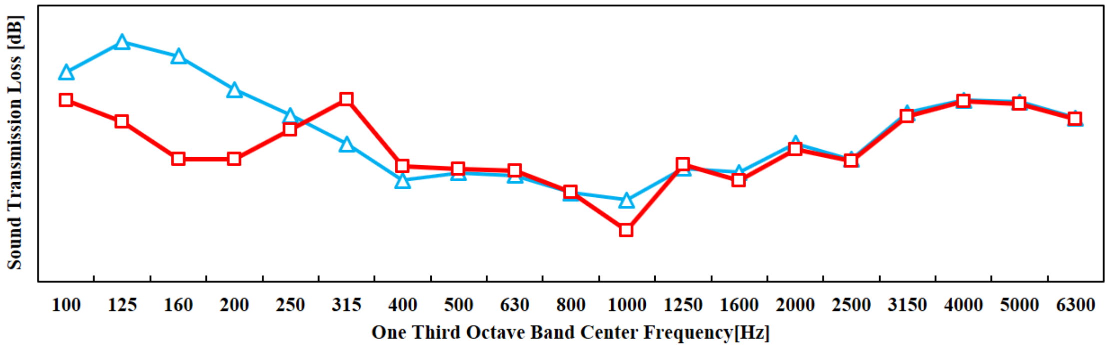


Fig. 8 – STL prediction results of wiring grommet: with wiring harness (blue triangle) and without wiring harness (red square).

Third, the effect of the wiring harness modulus on the STL of the wiring grommet was investigated. As the modeling was based on the equivalent modulus of the wiring harness, the effect of the Young's modulus of the wiring harness on the STL of the grommet was investigated. The following equivalent Young's moduli of the wiring harness were used for comparison: E_0, $2E_0$, and $0.1E_0$. In all the three cases, the effect on the STL of the wiring grommet is found to be negligible, as shown Figure 9.

In the case of $0.1E_0$, the STL was calculated to be 1.5 dB lower at a one-third octave band with center frequency of 1000 Hz. No significant STL differences were seen in the other frequency ranges. This is because the modulus of the wiring harness is much higher than that of the grommet even when the modulus is 0.1E_0. Thus, it does not affect the contact element stiffness.

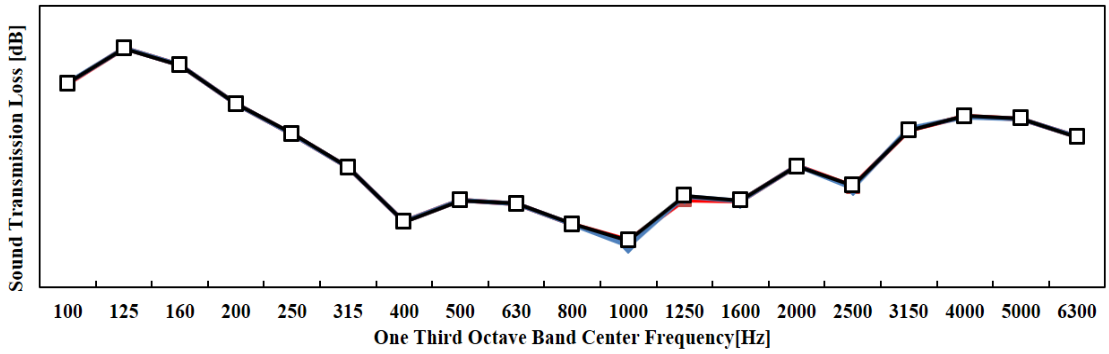


Fig. 9 – STL prediction results of wiring grommet with respect to different Young's moduli of the wiring harness: 2E_0 ( ), E_0 ( ), and 0.1E_0 ( ).

Additionally, the STL of the wiring harness exposed outside the grommet was calculated. A distributed plane wave was applied to the wiring harness exposed to the reverberant room, and the acoustic energy radiated through the wiring harness exposed to the semi-anechoic room was calculated to obtain the STL of the wiring harness. When the moduli of the wiring harness are E_0 and 0.1E_0, the STL of the wiring harness is higher than that of the grommet combined with the wiring harness, as shown in Figure 10. The minimum difference was 14 dB at a center frequency of 4000 Hz; however, considering the area of the wiring harness, the influence of the STL of the wiring harness on the STL of the wiring harness was negligible.

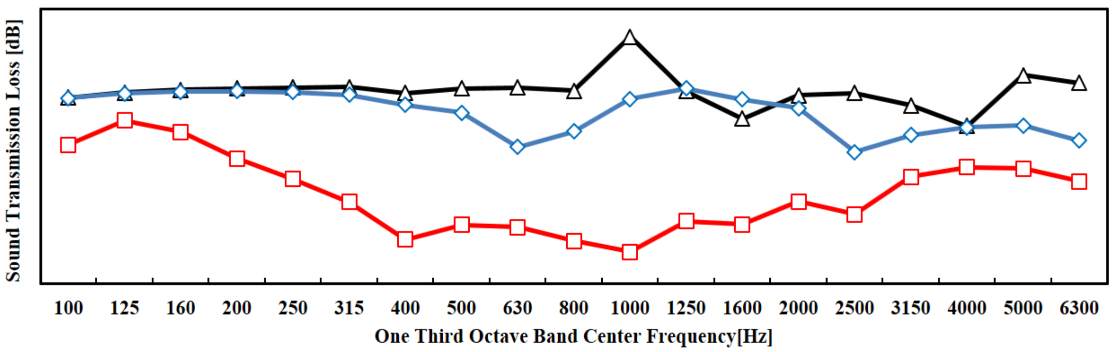


Fig. 10 – STL prediction results of wiring harness: E_0 ( ), 0.1 E_0 ( ), and STL of wiring grommet ( ).

5.3 Numerical Results

Figure 11 shows the numerical and experimental STL values of the wiring grommet. The measured modulus and DLF were applied, and the equivalent Young's modulus of the wiring harness was used. The stiffness of the contact element was calculated by setting the offset of the wiring harness to 1 mm. The highest discrepancies can be observed at a center frequency of 630 Hz, and this difference corresponds to an STL of 7.3 dB. The mean error of the STL is 5.8 dB for the frequency range of interest, and the numerical results are in reasonable agreement with the measured data.

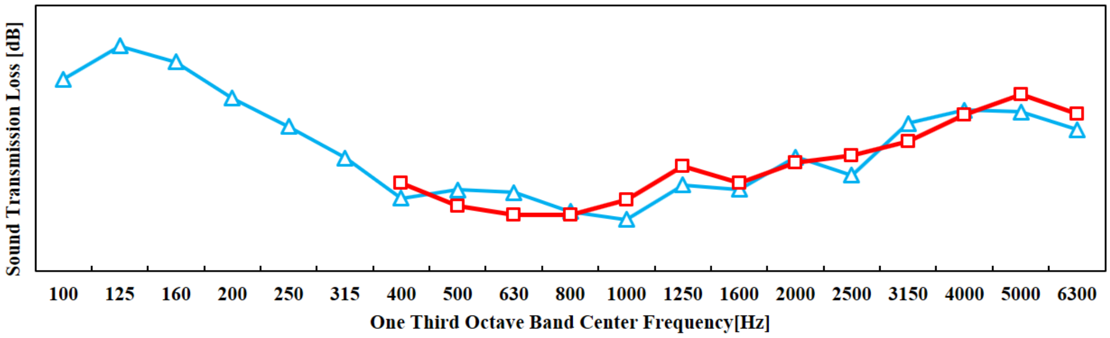


Fig. 11 − Sound transmission loss of the wiring grommet: Measurement ( ) and calculation ( ).

The reason for this discrepancy is that the boundary condition between the sound barrier fixture and the wiring harness may not follow the actual constraint, and the volume of the fluid cavity inside the wiring grommet may change because of the weight of the wiring harness.

6. CONCLUSION

In this study, a method of predicting the STL of a wiring grommet combined with a wiring harness was demonstrated using FEM. As a first step, a contact analysis was performed to model the dynamic behavior of the wiring grommet considering its coupling with the wiring harness.

As a second step, a fluid element was created, and an AML was applied to the fluid element face on the source and receiving sides for STL calculation. A parametric study showed that the wiring harness mainly affects the STL of the grommet in the stiffness-control region. However, the effects of the Young's modulus and the offset of the wiring harness on the STL of the wiring grommet were found to be insignificant.

Finally, the numerical and experimental STL values of the wiring grommet were compared to examine the validity of the modeling. The numerical STL of the wiring grommet was in reasonable agreement with the experimental results.

7. ACKNOWLEDGEMENTS

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