EVALUATION OF AUTOMOTIVE WEATHERSTRIP BY COUPLED ANALYSIS OF FLUID-STRUCTURE-NOISE INTERACTION

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Abstract. Automotive weatherstrip plays a major role in isolating the passenger compartment from water, dust and noise, etc. Among them, the wind noise through weatherstrip is the most severe factor making the passenger uncomfortable. Weatherstrip should be in contact between the door and the body frame, and sufficient contact area is needed to minimize the wind noise through weatherstrip. But there are several factors that make it difficult to ensure sufficient contact area. First, weatherstrip rubber deteriorates as time goes by and residual stress in the rubber becomes relaxed which results in the decrease of the contact area. Second, the gap between the door and the body increases due to pressure difference at high speed. In order to predict and reduce wind noise through weatherstrip, nonlinear behaviour of rubber at high speed and he effect of rubber deformation to wind noise should both be analyzed. In the paper, rubber deformation with time is obtained by hyperelastic and viscoelastic analyses, while the gap between the door and the body frame of the vehicle going at a high speed was predicted by the coupled analysis, Fluid-Structure Interaction (FSI). And also Statistical Energy Analysis (SEA) calculates the amount of wind noise numerically caused by rubber deformation under high speed condition.

1 INTRODUCTION

Car door weatherstrips have important functions like blocking noise transmission and foreign matter intrusion, as well as preventing vibration transmission. Recently, as the emotional perspective in vehicle performance evaluation has been emphasized, efforts to enhance sound insulation performance of door weatherstrip have increased (1-2). The double sealing method is currently used to improve sound insulation in vehicles that are semi-medium size or larger. The door seal, which is installed on the door frame, has sufficient pressure distribution with a deflection of approximately over 6 mm, so the impact it receives from door opening is small. However, the body seal, which is installed on the body frame, has a deflection of approximately 3 mm, so if the amount of door opening occurs more than that, the seal opens, reducing sound insulation performance.

Door opening refers to the phenomenon in which the door frame widens from inside out when pressure drops due to the vehicle's external flow at high speed, and is greatly influenced by the angle of the A filler. That is, the larger the A filler's angle, the bigger the change in external flow, which causes the door frame to widen.

This paper introduces an analytical prediction method for the sound insulation performance of the door weatherstrip by considering door opening effects. Fluid-Structure Interaction (FSI) analysis was used to predict the deformation of a door weatherstrip, which occurs due to the pressure difference between the inside and outside of a vehicle at high speed. Statistical Energy Analysis (SEA) was applied to evaluate the sound insulation performance when the weatherstrip is opened. Also, FSI analysis was conducted by considering the aging and permanent deformation of EPDM rubber, which is the main material of the weatherstrip, and the influence that these characteristics have on sound insulation performance were evaluated.

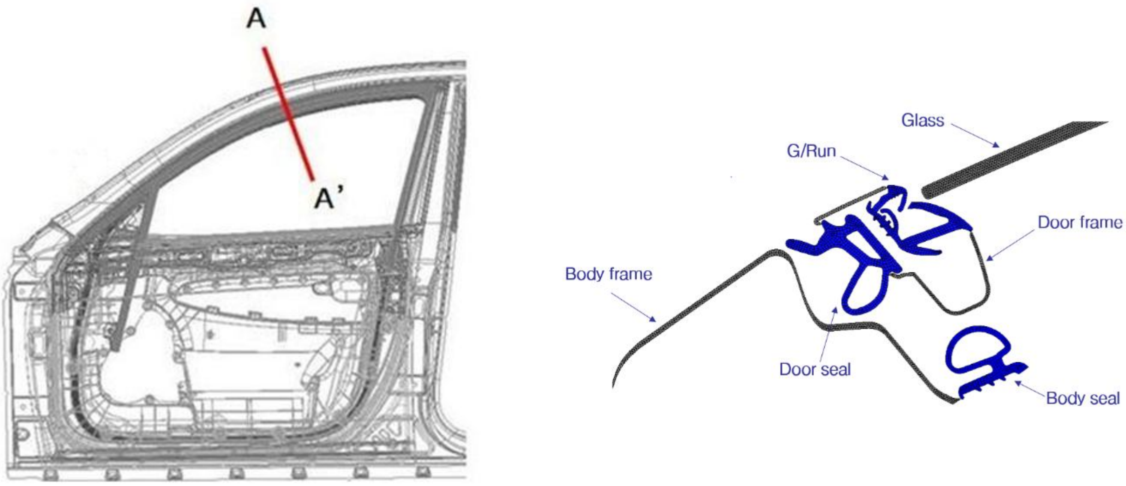

Figure 1: Illustration of the door and target point.

2 WEATHERSTRIP DEFORMATION PREDICTION USING FSI ANALYSIS

FSI analysis (4) was applied to predict the weatherstrip deformation which occurs when driving at high speed. The analysis was conducted using ADINA®, a commercial program. The cross section of a door, including the weatherstrip, was selected as the analysis model, see Fig. 1. As the part where the A filler and loop area meets, the cross section A- A' is where door opening most frequently occurs.

2.1 Finite Element Modeling

After conducting window installation and closing analysis, a two-dimensional cross section was modeled to predict the air flow when weatherstrip deformation occurs by dividing the vehicle into the car frame and seal and the fluid area. Car components like the body frame and seal used 1 mm 3-node elements and 4-node elements, whereas the fluid (air) area was modeled using 1 mm 3-node elements. The materials model of the seal applied the stress-strain curve obtained from the uniaxial tension test, and its behavior was expressed by considering the hyper elasticity model. Ogden model (4-6) was used as the energy equation, and the stress-strain curve is as shown in Fig. 2. Being air, a density of 1.983e-08 kg/mm3, and viscosity of 1.205e-12 N . s/mm2 was applied to the fluid area.

To considering door opening, the analysis was divided into the window installing procedure and door closing procedure, as shown in Fig. 3. Fixating the body frame and body seal, the installation analysis of the window was conducted in step 1, while door closing was simulated by moving window, glass run, and door seal in step 2. Finally, in step 3, to consider door opening, an analysis was conducted by moving models, which were moved when closing the door, on the Y axis from 0.5 mm to 3 mm at a 0.5 mm interval. Because the axis of flow direction and the axis of the analysis model cross section were different, the pressure value, instead of the fluid speed, was applied to analyze external flow following high speed driving. Using the data in the references, pressure was applied to the inside of the car as much as the amount reduced from the outside, and the amount of pressure change that occurs at the door loop area when driving at a high vehicle speed (180 km/h) is approximately -1000 Pa, as shown in Fig. 3 (3).

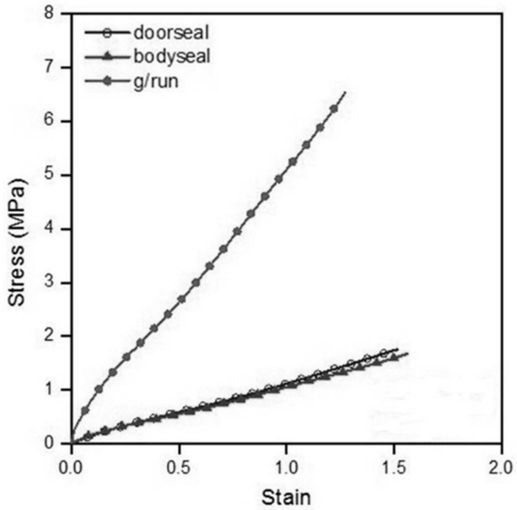

Figure 2: Stress-strain curve of seals.

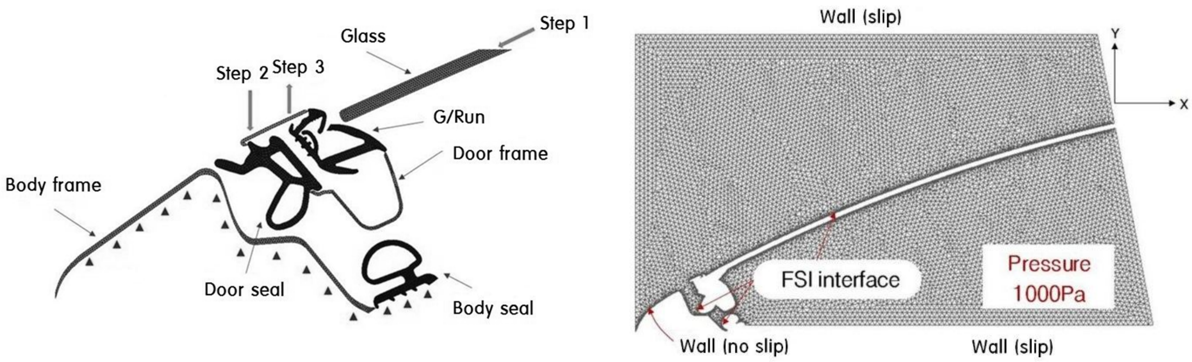

Figure 3: Boundary condition of the structure and fluid model.

2.2 Analysis Result

When moving the door outwards at a 0.5 mm interval, the door seal and body seal both maintained contact up to 2.5 mm, but at the door opening condition 3 mm, the body seal was separated from the frame due to fluid flow, as shown in Fig. 4. Also, the fluid inside escaped through the open space between the body frame and body seal. Fig. 5 shows the result of measuring the reaction force of the body frame on the body seal during the analysis time. At the door opening condition 3 mm, contact was maintained, but when pressure was applied in the interior space, the reaction force was eliminated.

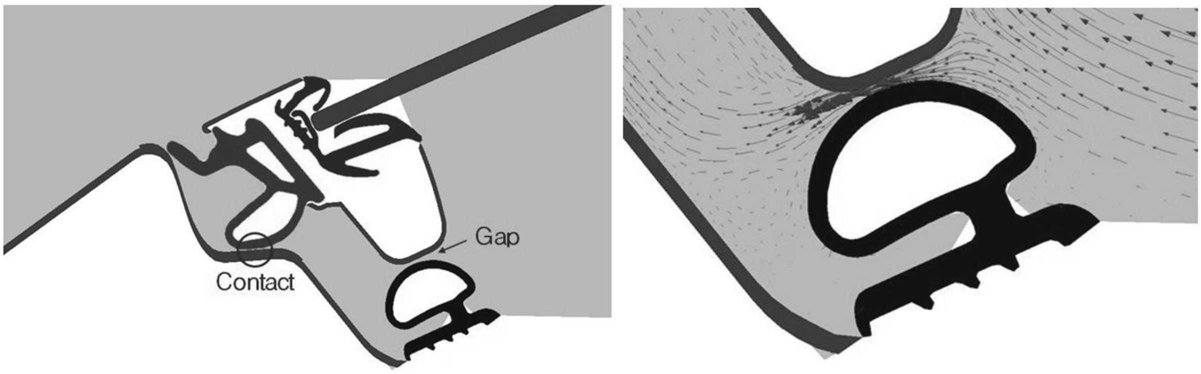

Figure 4: Analysis result of door open condition. (3 mm-open)

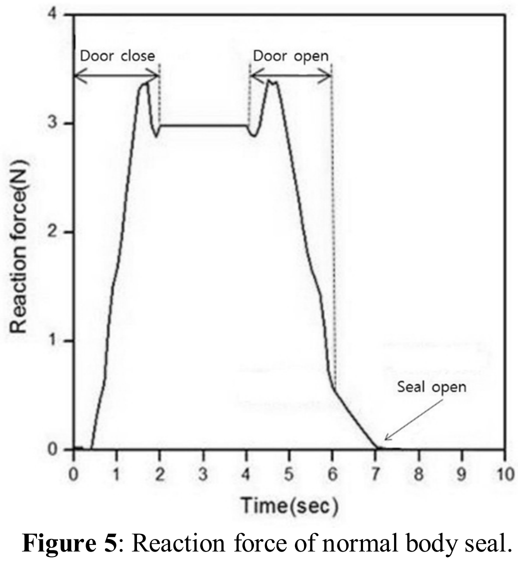

Figure 5: Reaction force of normal body seal.

3 WEATHERSTRIP WITH AGING OR PERMANENT DEFORMATION

To predict the permanent deformation, a weatherstrip was aged for long time in high temperature chamber. Compared to the stiffness obtained from the material tests of an initial product sample, the aged sample had approximately 40% lower stiffness (6). Also, to obtain the deformed door seal shape, the viscoelasticity analysis was conducted in time domain.

In case of the aged and permanently deformed model, the body seal was opened at door opening condition 2 mm. The reaction force was decreased by 50% compared to the initial state as shown in Fig. 7. Considering that the amount of permanent deformation on the body seal, it was confirmed that change in form, rather than the change in material stiffness, is a major factor of body seal opening.

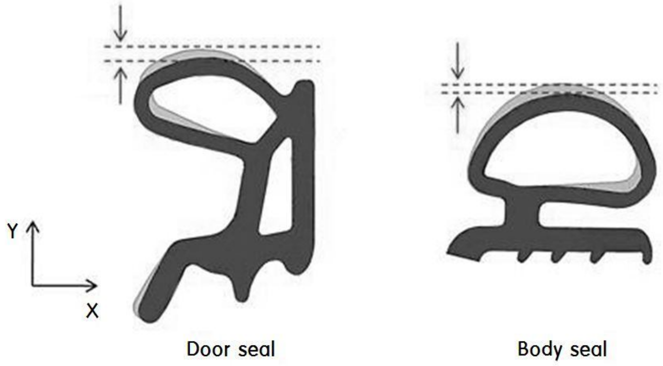

Figure 6: Measurement of permanent deformation.

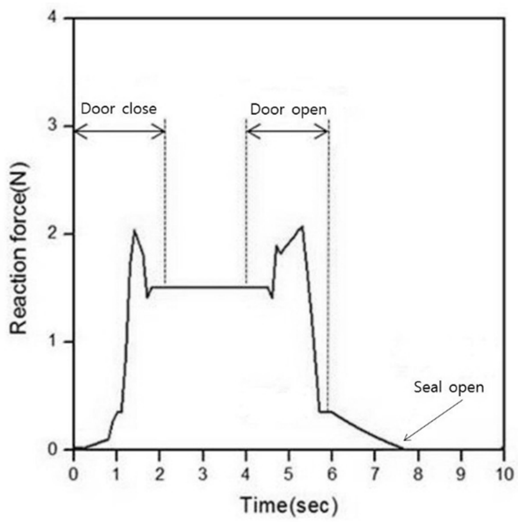

Figure 7: Reaction force of aging body seal.

4 EVALUATION OF SOUND INSULATION USING SEA

Generally, it is impossible to evaluate the response characteristics on the entire system using FEM and BEM because many modes exist in the high frequency range. Also, the accuracy of the results, which is based on element size and analysis time, decreases the analysis efficiency when using FEM and BEM due to using many elements (1,7). On the other hand, SEA is appropriate for noise analysis at high frequency range, which has large number of vibration modes. Also, it is a very practical method for analyzing the noise of the entire system, rather than individual parts which form the system. The basic principle of SEA is that it divides the analysis system into subsystems, and computes the energy transmission and loss between each system, as shown in Fig. 8 (1,7). Many vibration modes exist in the case of door seal sound insulation evaluation analysis, and because the goal is a sound insulation performance evaluation at the high frequency range of over 1000 Hz, SEA was used (9).

As shown in Fig. 9, the models for evaluation of sound insulation were obtained from the final shapes of the FSI analysis for the initial state and permanently deformed body seals under the given opening condition. The sound insulation performances in these two cases were then compared to each other. The modeling of cross sections with various thicknesses was done by using several components. After generating a three dimensional model by extruding a two dimensional shape to a certain length in the machine direction, the spaces between the frame and door weatherstrip were defined as subsystems in the SEA model (7). Also, a junction was defined for each subsystem (9). External sound pressure was decided by using the sound pressure measured in the door loop area inside the car during the wind tunnel test. Because the measured interior sound pressure was 73.3 dB, the measured result and analyzed result of the sound pressure transmitted inside were identical when the external sound pressure was 112.7 dB. Therefore, when the body seal was separated from the frame, sound pressure transmitted to the interior was evaluated by setting the external sound pressure condition at 112.7 dB.

The SEA result is shown in Fig. 10. In the case of the shape after aging, where the body seal is apart from the frame, the sound pressure transmitted to the interior was 85.1 dB. As shown in Table 1, the noise transmissibility increased approximately 10% compared to the initial state, in which the body seal was in contact with the frame. Therefore, it was confirmed that the most important factor in sound insulation performance evaluation was whether or not the body seal and frame were in contact.

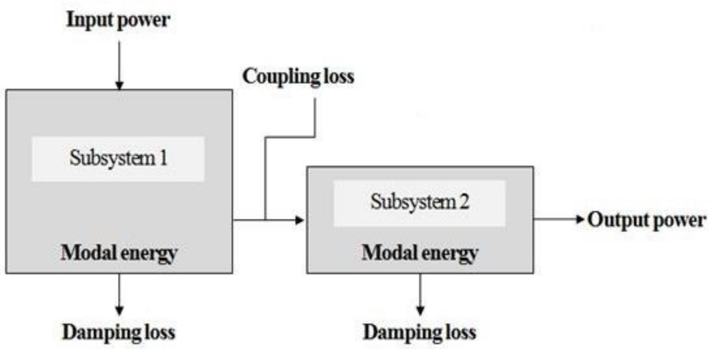

Figure 8: Boundary condition of the structure model.

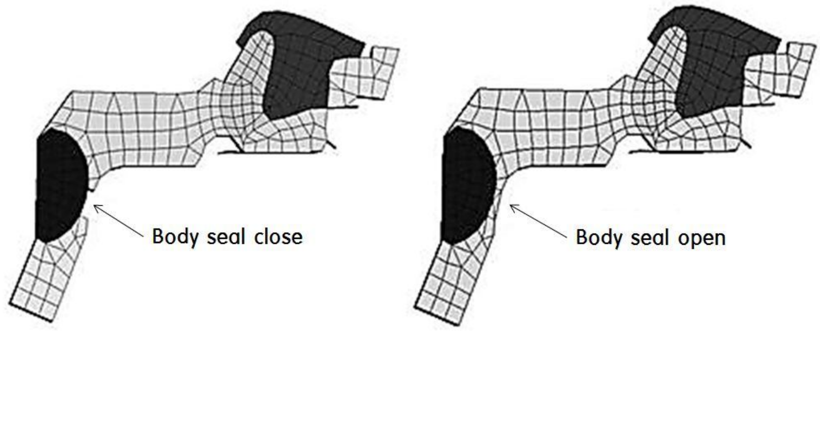

Figure 9: SEA model.

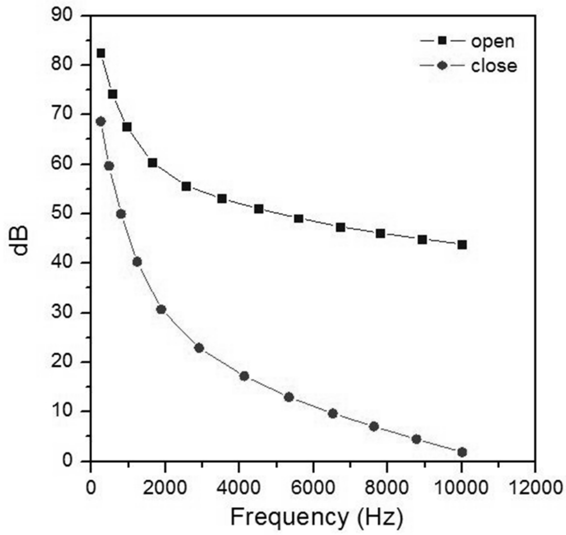

Figure 10: Comparison of sound pressure for two scenarios.

Table 1: Comparison of sound pressure for two scenarios

	Seal close (Initial state)	Seal open (Aged state)
Average sound pressure (dB)	73.3	85.1
Noise transmissibility (%)	65.0	75.5

5 CONCLUSION

This paper proposes an analytical method for evaluating sound insulation performance of a door weatherstrip by considering door opening. Door weatherstrip deformation caused by external pressure drop at high speed was identified through FSI analysis, and characteristics were compared to understand the effect of aging and permanent deformation of the material. Also, by using SEA to comparatively evaluate sound insulation performance when there is/isn't body seal contact, it was found that whether or not there is contact with the frame following permanent deformation of the door weatherstrip is an important factor for sound insulation performance.

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