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Development of a Method for Predicting Door Closing Sound Sensory Scores in the Design Phase Using CAE and AI

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The door closing sound is a significant factor that greatly influences the overall impression of a vehicle. However, in recent years, vehicle weight reduction has had an adverse effect on door closing sound quality. In addition, in compact vehicles, there are many constraints on applying sound-enhancing measures, making this tendency even more pronounced. Thus, the quality of the door closing sound is strongly affected by vehicle structure and design conditions. Although we have conducted CAE analyses, we relied heavily on evaluations using spectrograms of door closing sounds obtained through time-varying loudness analysis (Fig.1) and the sensory evaluation of skilled evaluators. As a result, there were challenges in improving sound quality from the design stage. Therefore, we undertook the development of a methodology that enables door closing sound evaluation and quality improvement from the early stages of vehicle design.

To develop a prediction method for door closing sound sensory scores, two major initiatives were undertaken.

First, in order to predict the door closing sound spectrogram using CAE, nonlinear structural analysis and transient acoustic analysis were coupled, with the analysis focusing solely on the sound radiation from the outer door panel. The analysis was conducted on two cases: the “Original door” and the “Modified door,” in which the properties of the mastic material were changed. In the nonlinear structural analysis, the door closing event was reproduced, and the acceleration of the outer door panel was calculated. To ensure accurate vibration reproduction, the nonlinear characteristics of components such as the weatherstrip and the door lock were defined based on experimental measurements. In the transient acoustic analysis, the calculated acceleration was used as input to compute the sound pressure. As a result, the CAE predictions were found to satisfy approximately 70% of the evaluation criteria. Furthermore, a comparison of the door closing sound spectrograms between the Original door and the Modified door showed trends consistent with those observed in actual measurements.

Second, an AI model was constructed to determine the sensory score of door closing sound—categorized into eight levels ranging from 1.0 to 4.5 in 0.5-point increments—using CAE-predicted spectrogram images and the corresponding numerical features as input. Because door closing sound data needed to be collected from different vehicle models, the dataset was limited to approximately 500 samples. Targeted feature engineering approaches were implemented during model development to ensure high-accuracy scoring even with this small dataset. We created features by applying image and numerical processing, incorporating the knowledge of skilled evaluators, and generating interaction terms between features. To avoid overfitting and to achieve stable predictions even with limited data, we adopted a Random Forest classifier. Furthermore, to improve prediction accuracy, we analyzed misclassification samples and employed a genetic algorithm for feature exploration, which successfully increased the accuracy to 0.86. For interpretability of the prediction results, we introduced LIME, thereby clarifying the rationale behind the predictions through the predicted probability of the sensory score and the contribution of each feature.

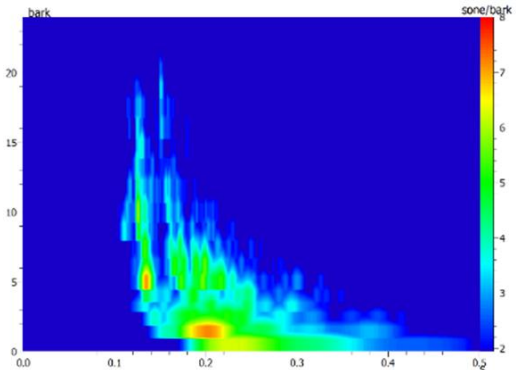

Fig.1 Door Closing Sound Spectrogram

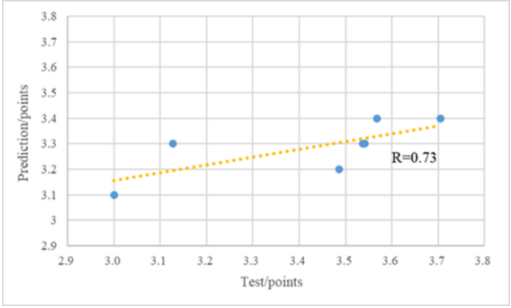

Fig.2 Correlation of Sensory Scores

In the effectiveness verification of a door closing sound sensory score prediction method that combines CAE and AI, a strong correlation was confirmed between measured sensory scores and predicted scores, with a correlation coefficient of R = 0.73 (Fig.2) for seven vehicle models, including Kei cars, A-segment, and B-segment classes.In this study, we developed a method to estimate sensory scores by inputting spectrograms obtained from CAE analysis into an AI model and verified its effectiveness.Going forward, we aim to utilize the developed method to improve door closing sound quality from the early design stage.