

Development of a Real-Time Sound Prediction System and Its Application to Steering Gearbox Noise Evaluation

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To achieve front-loading in steering gearbox NVH development, a bench evaluation environment capable of capturing sound variations arising from subtle differences in steering input is required. This paper first verifies, through offline transfer path analysis (TPA), the feasibility of replacing vehicle-based evaluation with bench-based evaluation for steering gearbox noise. Next, the challenges associated with implementing the TPA-based prediction process in real time are investigated, and a real-time acoustic prediction system is developed. Finally, the proposed system is applied to the evaluation of steering gearbox reversal noise. The results demonstrate good correlation between bench and vehicle evaluations, as well as good agreement in perceived loudness and timbre, confirming the effectiveness of the proposed approach.

As a prerequisite for real-time implementation, the bench replacement approach previously demonstrated for electric power steering operating noise is verified, through offline TPA calculations, to be applicable to the target noise, whose loudness and timbre vary with steering input. Component based TPA is employed. Blocked forces, which are intrinsic to the source component and can therefore be identified on a test bench rather than in a vehicle, are estimated from the inverse inertance matrix and the operational accelerations measured at the three gearbox mounting points in three directions. The identified forces successfully reproduce the measured fixture vibrations on the bench in both the frequency and time domains. Furthermore, when combined with the vehicle transfer characteristics to the driver's ear position, they predict a sound that closely matches the directly measured vehicle sound in frequency content, level, and timbre. These results confirm that vehicle-based evaluation can be replaced by bench-based evaluation.

Next, the key challenge in real-time implementation, namely achieving high prediction accuracy including perceptual sound quality while minimizing response delay, is investigated. FIR filters are derived from pre-measured transfer functions and implemented using the Overlap-Save convolution method, while data acquisition, TPA computation, and audio output are executed in parallel threads. The filter length involves a trade-off between prediction accuracy and latency. A 1024-tap filter (43.1 Hz frequency resolution at 44.1 kHz sampling) reduces processing time but degrades perceived sound resolution, whereas a 4096-tap filter (10.8 Hz resolution) achieves good agreement with offline calculations above 300 Hz at the expense of increased delay. Since both configurations provide acceptable latency for noise evaluation, the filter length is made configurable according to the target noise characteristics. Fig.1 shows the resulting system configuration, consisting of accelerometers, a data acquisition unit, a PC, an audio interface, headphones, and the steering gearbox installed on a test bench.

Finally, the developed system is applied to reversal noise, one of the characteristic noises generated in a steering gearbox, using a gearbox whose specification can be adjusted across five levels. As shown in Fig.2, the bench and vehicle sound pressure levels exhibit strong correlation (correlation coefficient: 0.89), although the bench results are slightly higher because of environmental factors such as operating noise from the test bench. Across all specification levels, the perceived loudness, timbre, and steering-dependent sound variations closely match those observed in vehicle evaluations. These results demonstrate that vehicle-equivalent evaluation can be achieved on a test bench. Future work includes extending the approach to other types of steering gearbox noise and to additional components evaluated through acoustic performance.

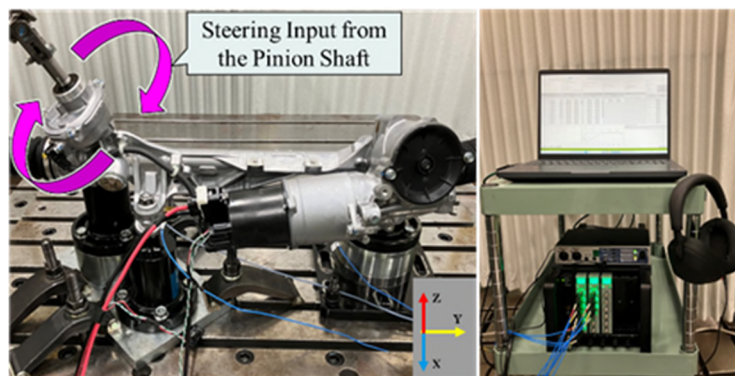


Fig.1 Test Bench Setup and Real-Time Noise Prediction System

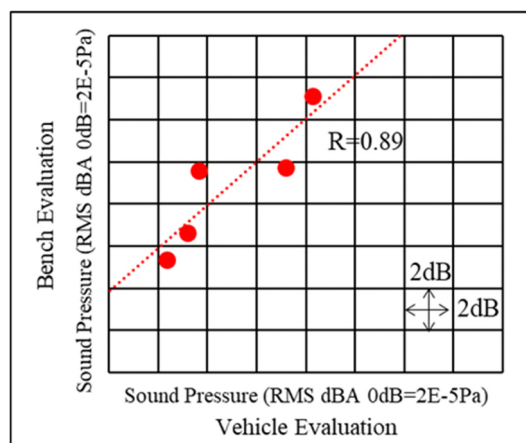


Fig.2 Comparison of Sound Pressure (RMS) Between the Vehicle Evaluation and Bench Evaluation