

Enhancement of Diesel Combustion Noise for Interior Sound Quality

– Transfer Path Analysis Using Principal Component Regression Method –

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ABSTRACT

An analysis focusing on the transfer paths of combustion noise from the engine to the interior of the cabin was conducted in order to enable enhancement of audible in-cabin diesel combustion noise during the development of the 2009 model year ACCORD diesel. Transfer path analysis using the principal component regression method was employed to analyze the degree of contribution to noise transfer. First, the airborne and structure-borne contribution for 920-2300 Hz radiation noise, which represents an issue from the perspective of combustion noise, was analyzed. Following this, the input paths for the structure-borne component were determined. As a result, it was judged that despite the fact that airborne transfer has been regarded as the major factor in the case of the high-frequency band, the structure-borne component also has a profound effect. Methods of enhancing interior sound were examined based on the results of the contribution analysis. Reducing the transferred components by controlling vibration in the mounts has enabled enhancement of combustion noise in the cabin.

1. Introduction

Today, diesel engines for use in passenger vehicles are necessary to produce high power, display high fuel efficiency, and conform to stringent exhaust gas regulations. From the perspective of the commercial appeal of the vehicles in which the engines are fitted, low noise and measures for the enhancement of interior sound quality represent further necessities.

In diesel engines, the noise with the greatest effect on interior sound quality is diesel combustion noise (“combustion noise” below) originating in combustion excitation force. Conventionally, combustion tuning by means of using a pilot injection and a main injection in order to reduce the combustion excitation force has been the main method of enhancing combustion noise. However, the enhancement of noise by means of combustion tuning is antagonistic to the achievement of increased fuel efficiency and reduced exhaust gas emissions, and the margin for the use of this method in reducing noise is declining with increasing demands from the market for enhanced fuel efficiency and conformity with more stringent emissions regulations.

In order to determine measures for the enhancement

of interior sound quality that do not rely on combustion tuning, the research discussed in this paper focused on measures targeting the transfer paths of noise. The project applied the principal component regression method to transfer path analysis⁽¹⁾ (a method that is termed “PCR-TPA” below). The results showed the structure of the engine mounts in the transfer path to be a major factor in the transmission of engine noise, and that the control of vibration in the mounts has enhanced combustion noise.

2. Nature and Characteristics of Combustion Noise, and Countermeasures Instituted to Date

In the vehicle interior, combustion noise generates rattling and clinking noises of fluctuating intensity. The range and level of these sounds varies with variations in the engine speed and load and the temperature of oil and intake air.

Figure 1 shows the results of an analysis of interior sound quality. The graph shows a comparison of interior sound quality with higher and lower level of combustion noise in a completed vehicle.

The vertical axis of Fig. 1 shows fluctuation intensity,

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an index of sound quality formulated and quantified by Honda^{(2),(3)}, while the horizontal axis shows the auditory critical band⁽³⁾.

Figure 1 shows that combustion noise is a noise that is generated within the high-frequency band between 920 and 2300 Hz (in this paper, 920 Hz and above will be termed “high-frequency”).

Conventionally, the use of sound insulating materials and acoustic insulators to dampen airborne transfer of noise has been the main method of reducing high-frequency interior noise. This is because it has been considered that, at frequencies of over 1 kHz, the higher the frequency becomes, the lower the effect of structure-borne transfer that is due to the mutual effect of declining body sensitivity and declining amplitude of vibration. Insulating materials and acoustic insulators have therefore been employed during development as an effective countermeasure against noise.

However, there have been cases during vehicle development in which the use of additional insulating materials and acoustic insulators has not resulted in an enhancement satisfying interior sound quality requirements. Recognizing the necessity for a thorough analysis of the input paths for combustion noise to the vehicle interior, the project discussed in this paper therefore set out to conduct analyses using PCR-TPA.

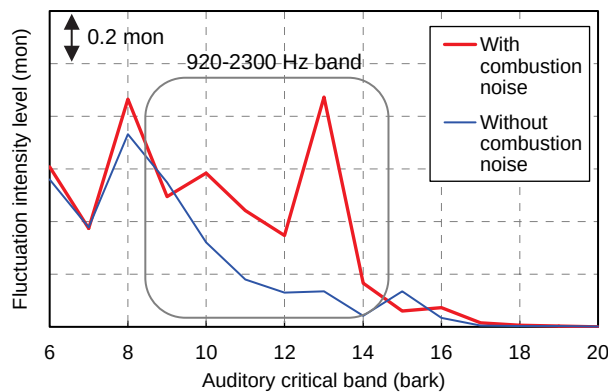


Fig. 1 Interior sound quality

3. Vehicle Interior Sound Analysis using PCR-TPA

3.1. Characteristics and Measurement Method of PCR-TPA

To date, a number of methods have been proposed for use in the analytic technique of transfer path analysis. The majority of these proposed methods have involved simultaneous measurements of structure-borne and airborne noise components in an operating vehicle. However, the separation of these components represents a challenge. When the sound pressure signal at a single

point between the engine and the vehicle body is used as a reference to enable determination of the effect of the engine radiation noise (the acoustic excitation force) on the vehicle body (the structure), even when the sound pressure signals at the reference point are identical, the excitation force transmitted to the structure can differ as a result of differences in the direction of the sound waves or the magnitude of the sound source. In such cases, the inability to accurately understand the effect of the excitation force can prevent the calculation of an accurate transfer function from the sound pressure signal at the reference point and the interior sound at the response point. Impact tests using dummy sound sources have generally been employed in order to address this issue. When researchers wish to conduct high-precision measurements of the structure-borne and airborne components of interior sound, it is necessary to utilize both impact tests and actual running tests, and this can be impractical.

PCR-TPA has been proposed⁽¹⁾ as a method of separating and analyzing components when vibration and noise have been measured simultaneously in vehicle tests. The present project employed PCR-TPA, considering that its use in contribution analyses would enable the accurate separation of airborne and structure-borne components, and the consequent clarification of the input paths of combustion noise to the vehicle interior. (Contribution analysis is a method in which the ratios of the airborne and structure-borne components of interior sound obtained through transfer path analysis are calculated.)

Measurements were conducted in a 2008 model year Accord, a 4-door sedan fitted with an inline 4-cylinder diesel engine. With regard to data measurement points, considering both solid transfer paths for excitation force and airborne transfer paths for acoustic excitation force, reference points for vibration and sound were established in the pathways shown in Fig. 2; a dummy head microphone was positioned in the front passenger seat,

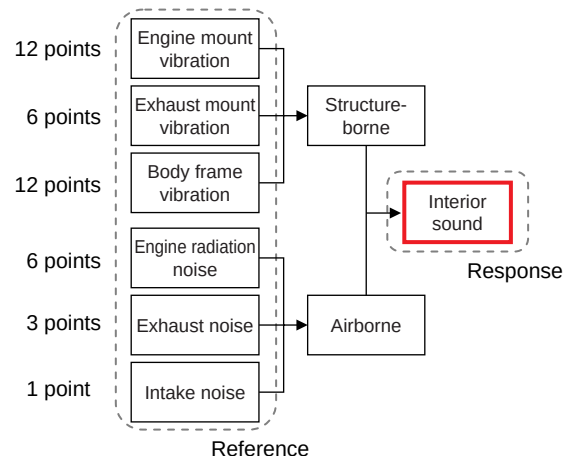


Fig. 2 Measurement setup for PCR-TPA

and response points were located at the left and right ears of the dummy. The vehicle was placed in a test jig, and simultaneous measurements were conducted at all reference and response points while the engine load conditions were varied.

Combustion varies with variations in load and temperature conditions in diesel engines, and these variations produce variations in sound quality. In order to study sound quality in relation to all these variations, the present project conducted analyses both during and after warm-up. Here, an engine water temperature of 60°C is the starting condition for measurements “during warm-up,” and an engine water temperature of 80-85°C is the starting condition for measurements “post-warm-up.”

3.2. Airborne and Structure-borne Components

Figure 3 shows the results of separation of the airborne and structure-borne components of synthesized post-warm-up vehicle interior sound using PCR-TPA.

The results show that the contribution of the structure-borne component is high for noise in the 920-2300 Hz band, the combustion noise range.

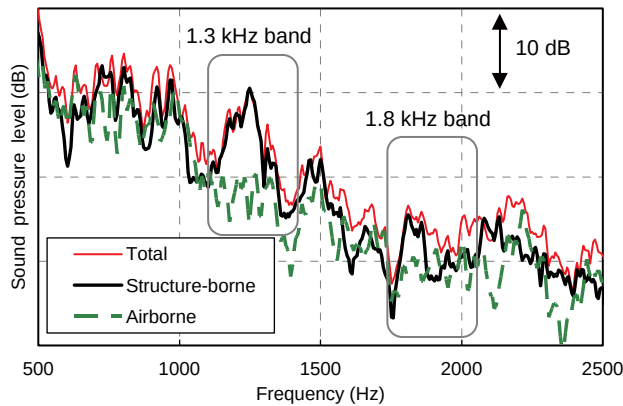


Fig. 3 Comparison of structure-borne and airborne contribution for in-cabin noise

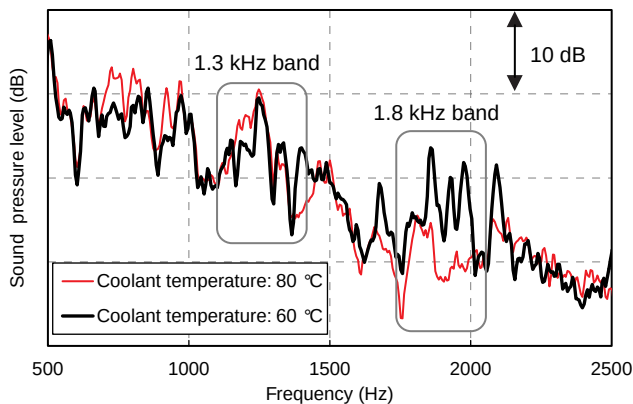


Fig. 4 Comparison of structure-borne noise by engine cooling water temperature

The contribution of the structure-borne component is particularly high in the 1.3 kHz and 1.8 kHz bands. As Fig. 4 shows, there is a significant change in the sound pressure level from warm-up to post-warm-up in the 1.8 kHz band.

3.3. Identification of Vibration Input Pathways

The results of the analysis of transfer paths indicated that the transmission mounts (Tr-Mt) and the upper torque rod mounts (Up-Mt) displayed the highest contribution of all the engine mounts (“Mt” below). The results also showed that there was a change in the noise transmission level from warm-up to post-warm-up for the Up-Mt. Figures 5 and 6 respectively compare the structure-borne component of the Tr-Mt and the structure-borne component of the Up-Mt with the total structure-borne component of interior sound.

Within the 1.3 kHz band, there is a range in which the contribution of the structure-borne component of the Tr-Mt is high, and which has a significant effect on interior sound. The level of input from the Tr-Mt changes only minimally from warm-up to post-warm-up.

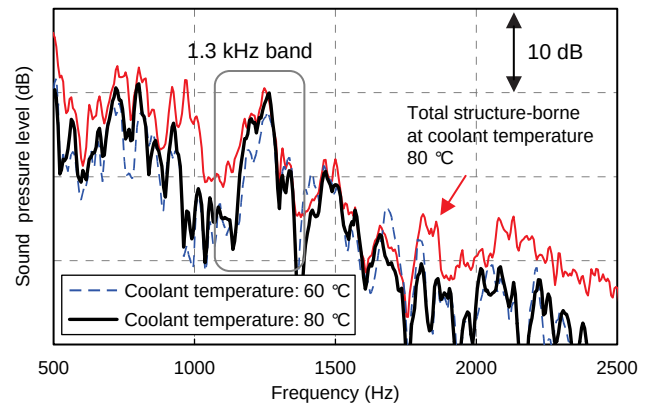


Fig. 5 Tr-Mt contribution to structure-borne noise

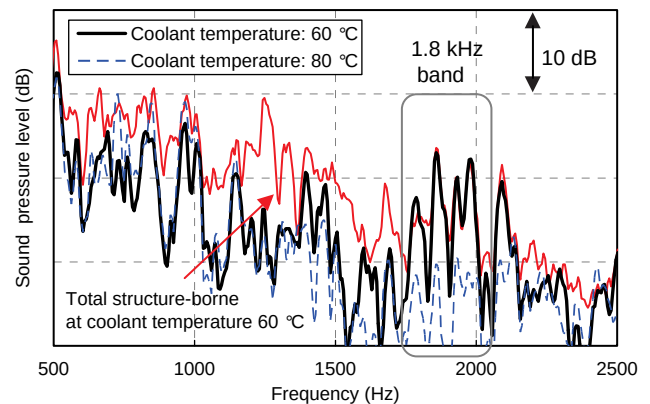


Fig. 6 Up-Mt contribution to structure-borne noise

Within the 1.8 kHz band, there is a range in which the contribution of the structure-borne component of the Up-Mt is high, and which has an effect on interior sound during warm-up. A change is observable in the level of the structure-borne component from the Up-Mt between warm-up and post-warm-up.

The reason for this change in the level from the Up-Mt is believed to be the fact that the high-frequency component of combustion, which is the excitation force, changes between warm-up and post-warm-up. Because the characteristics of the transfer paths that are affected by this change in the high-frequency excitation force have not been clarified previously, effective countermeasures for combustion noise within the transfer paths have not been implemented. The analysis discussed here indicated the existence of a structure-borne component in the high-frequency component of interior sound, identified the transfer paths, and indicated that the structure-borne transfer paths change with changes in combustion. These results enabled the study of effective countermeasures against noise in the transfer paths. The project went on to study methods of reducing combustion noise via countermeasures introduced into the transfer paths.

4. Study of Methods for Reduction of Vibration Input and Enhancement of Sound in Completed Vehicle

4.1. Measurements of Reductions in Interior Noise

The transmitted noise components obtained via PCR-TPA were resynthesized as interior sound after changes were made to the characteristics of each transfer path, and the resynthesized sound was evaluated by means of listening tests and sound quality analysis in order to enable the formulation of targets for interior sound.

Figure 7 shows a comparison of the results of sound quality analysis of interior sound measured in an actual vehicle and the interior sound obtained from resynthesizing components. The results for the resynthesized sound were obtained after changing the 1.3 kHz band of Tr-Mt vibration.

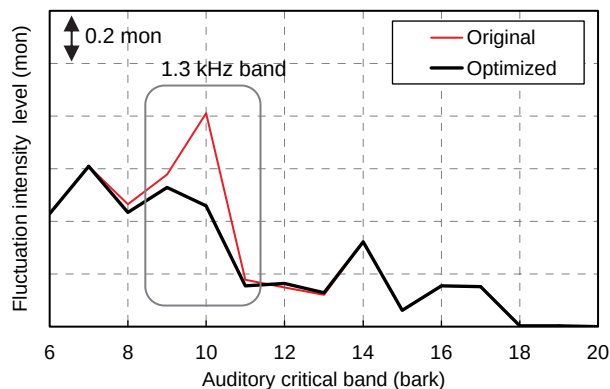


Fig. 7 Target value for optimized interior sound

The results indicated that changing Mt vibration changes the quality of combustion noise, and clarified the level of reduction that could be made a target. The level of reduction for the Up-Mt was clarified in the same way.

4.2. Reduction of the Structure-borne Component for the Mount Brackets

Analyses indicated that the forms of the Tr-Mt and Up-Mt engine mount brackets ("BRKT" below) were factors in the change in vibration within the transfer paths.

Chiefly due to the dynamic characteristics resulting from their form, the BRKT increase and decrease vibration input from the engine. Research was conducted on a method of using this characteristic in order to enhance interior sound quality by reducing vibration in the high-frequency range.

Figures 8 and 9 respectively show the Tr-Mt and the Up-Mt.

It was determined that the BRKT resonated with the frequencies that represented the issue. The following modes were identified:

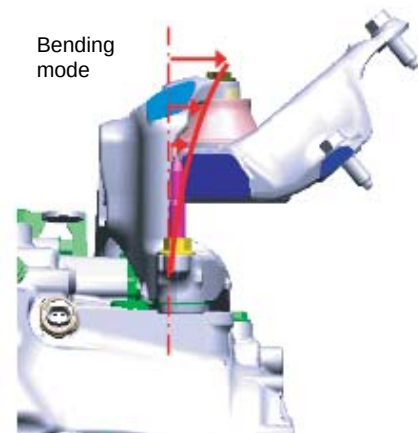


Fig. 8 Tr-Mt

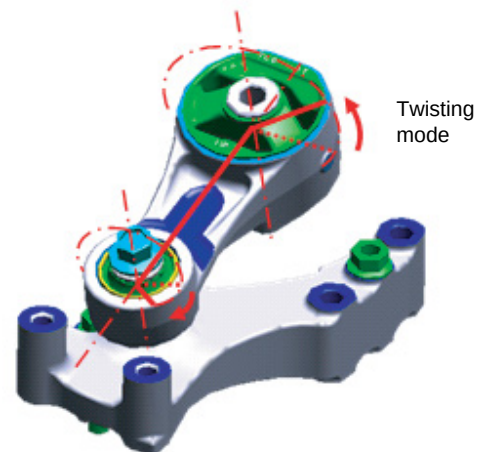


Fig. 9 Up-Mt

- (1) 1.3 kHz band: Tr-Mt BRKT right-left bending mode
- (2) 1.8 kHz band: Up-Mt BRKT twisting mode

Having identified the modes representing the major factors, measures to control vibration in each BRKT were applied in order to reduce response.

Figures 10 and 11 respectively show the results of the use of PCR-TPA to separate the structure-borne components of interior sound transmitted from the Tr-Mt and the Up-Mt before and after the application of countermeasures. Figure 10 shows results post-warm-up, while Fig. 11 shows results during warm-up.

The following enhancements in the structure-borne component of interior sound from each Mt were obtained:

- (1) The 1.3 kHz-band structure-borne component from the Tr-Mt was reduced by approximately 15 dB
- (2) The 1.8 kHz-band structure-borne component from the Up-Mt was reduced by approximately 10 dB

4.3. Verification of Enhancement in Completed Vehicle

As a final verification of the effectiveness of the countermeasures in enhancing sound quality, interior

sound measurements were conducted in completed vehicles with and without the application of the countermeasures.

Figure 12 shows the results of these measurements of combustion noise in the vehicle interior. The measurements shown in Fig. 12 were taken during warm-up.

Control of the vibration of the engine Mt BRKT, the transfer path, resulted in an enhancement in the fluctuation intensity of combustion noise in the vehicle interior in the 920-2300 Hz band. The reductions were particularly significant in the 1.3 kHz band (10-11 Bark) and the 1.8 kHz band (13 Bark). The application of the countermeasures resulted in the reduction of structure-borne components between 920 and 2300 Hz, the range in which combustion noise is audible in the vehicle interior, and enhanced the comfort of the vehicle interior.

These results have demonstrated that the control of structure-borne components is an effective means of enhancing combustion noise.

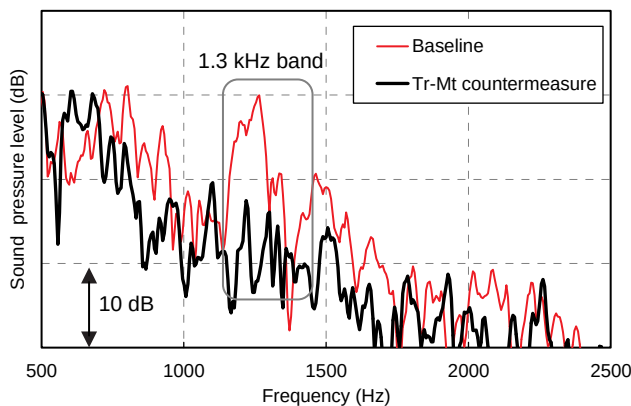


Fig. 10 Effect of Tr-Mt countermeasure on Tr-Mt's structure-borne contribution to interior sound

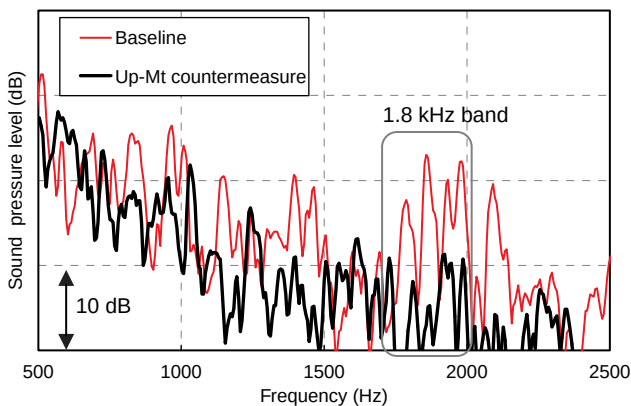


Fig. 11 Effect of Up-Mt countermeasure on Up-Mt's structure-borne contribution to interior sound

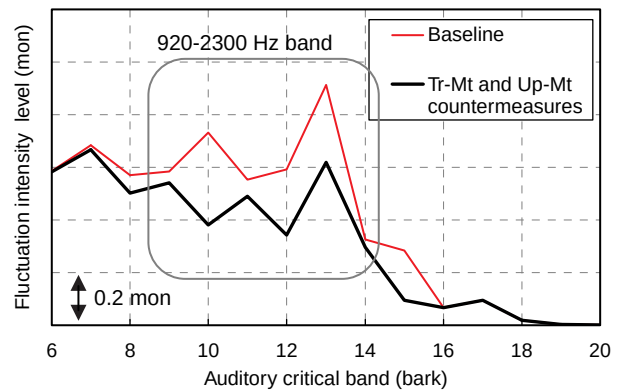


Fig. 12 Results of analysis of interior sound

5. Conclusion

The following results were obtained from the application of transfer path analysis:

- (1) The study indicated that in addition to airborne components, structure-borne components also have an effect on the diesel combustion noise audible in the vehicle interior.
- (2) Control of the vibration of the engine mounts reduced the level of the structure-borne component, and enhanced the comfort of the vehicle interior in terms of combustion noise.
- (3) The study indicated that PCR-TPA is an effective method of analyzing combustion noise.

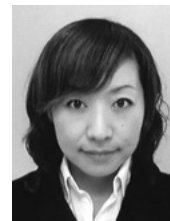
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