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NOISE CONTROL FOR A BETTER ENVIRONMENT

Investigating structure-borne noise propagation through powertrain mounts using operational transfer path analysis

Lu, Ming-Hung[1]
Jen, Ming Une[2]
Industrial Technology Research Institute
Bldg. 58, 195, Sec. 4, Chung Hsing Rd.
Chutung, Hsinchu, 31040, TAIWAN

de Klerk, Dennis[3]
Müller-BBM VibroAkustik Systeme B.V.
Veldweg 81
8051 NP Hattem, the NETHERLANDS

ABSTRACT

A previous study to improve the interior noise of an electric minivan identified that all order related noise up to about 1 kHz was caused by structural vibration. Therefore, this paper further investigates the vibration propagation through powertrain mounts using operational transfer path analysis (OTPA). The powertrain vibration was captured with accelerometers at left-hand motor mount, right-hand motor mount and propshaft mount—both body and active side. Such responses will characterize the active side excitation, mount isolation and the effect of structure-borne transfer paths on the interior noise. The OTPA synthesis results on powertrain mounts matched quite nicely with the measured responses. Through OTPA synthesis results, body side vibration of each mount was further separated as contributions from the active side of individual powertrain mounts. Analysis showed that most of the important interior noise contributions on individual mount were caused by vibration transmission though the mount itself. The vibration generated at the active side of propshaft was also transmitted very well through the other mounts. With operational measurements only and an appropriate choice of reference and response sensors, this study showed that different OTPA synthesis models can be built to determine which powertrain mount propagates most structure-borne noise to a vehicle cabin in general.

Keywords: Operational transfer path analysis, Structure-borne noise, Powertrain mount
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1. INTRODUCTION

Noise source and transmission path identification is an important development process on improving sound quality in vehicles at a later stage of refinement. To improve

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[1] minghung-lu@itri.org.tw
[2] mujen@itri.org.tw
[3] ddeklerk@muellerbbm-vas.nl

the vehicle interior sound perception, efficient measurement and analysis techniques to separate the contributions of airborne and structure-borne noise sources as well as their propagation paths into the cabin are essential. By tracing cabin noise back to specific components, engineers can target their mitigation efforts more precisely. While the chassis used for an electric vehicle (EV) was retrofitted from a conventional engine vehicle, the engine mounts were usually as carryover parts and used for vibration isolation. However, the dynamic stiffness characteristics of mounts for the engine powertrain may not achieve the desired vibration reduction for the electric powertrain. Aiming to examine structure-borne noise through powertrain mounts of an electric vehicle, this paper focuses at the powertrain mounts isolation and the effect of structure-borne transfer paths on the interior noise using operational transfer path analysis (OTPA).

To link interior noise with the contributions from different structure-borne paths, simulation analyses[1] or testings[2-3] or both can be employed. While several classical transfer path analysis methods, such as matrix inverse method[4] and reciprocal sound source measurements[5], are used to identify true sources and paths, the true benefit of the OTPA is that it determines the noise contributions from operational measurements only. With the actual excitation sources implicitly accounted for, OTPA[6,7] is an effective technique to separate contributions at the receiver's location from the radiated sound of sources and the structure-borne noise propagation. Additionally, the synthesis results by OTPA are beneficial to investigate the effect of individual transmission path on the interior noise. Since only operational measurements are required, OTPA reduces analysis time considerably allowing faster design iterations.

Bridging between the active side of powertrain and vehicle body, powertrain mounts usually are the most significant for improving interior structure-borne noise induced by the traction motor, gearbox and propshaft. In contrast to controlling airborne noise by sound absorption and insulation, redesigning a compromised dynamic characteristics of powertrain mounts requires more development efforts[3]. To precisely hit the target for refinement, a detailed OTPA is necessary to ascertain the vibration isolation characteristics of each mount, particularly the contribution from each mount.

Our previous study[8] to improve the interior noise of an electric minivan identified that all order related noise up to about 1 kHz was caused by structural vibration. To look into the suitability of powertrain mounts, this paper further investigates the vibration propagation through powertrain mounts using OTPA. The associated electric powertrain is isolated by three mounts—left-hand motor mount, right-hand motor mount and propshaft mount. As cabin noise along with vibration across individual mount were measured, responses of mounts' vibration were used to characterize the effect of structure-borne transfer paths on the interior noise. Based on validated OTPA synthesis results, the breakdown of structure-borne noise contribution indicates that most of the important interior noise contributions on individual mount were caused by vibration transmission though the mount itself. The vibration generated at the active side of propshaft was also transmitted very well through the other mounts. Overall, these results indicate that foremost powertrain structure-borne noise was on the vibration isolation issues of the mount itself. With an appropriate choice of reference and response sensors, this study showed that different OTPA synthesis models can be built to determine which paths transmit most structure-borne noise into a vehicle cabin.

In the following sections, we first recap previous main noise source separation results, then briefly describe the method of OTPA. After that, we highlight the breakdown results of structure-borne noise contribution, and finally conclude the work.

2. RECAPPING PREVIOUS MAIN NOISE SOURCE SEPARATION RESULTS

A rear-wheel drive commercial minivan originally equipped with a combustion engine and drivetrain was used to develop a prototype electric vehicle. Retrofitted and equipped with a newly developed electric powertrain, the vehicle studied was transformed as a two-seater passenger-cargo electric minivan. The newly developed 50 kW traction motor is with an 8-pole/60-slot configuration. The 50 kW traction motor with a single-speed gearbox is isolated by two carryover rubber mounts on its left-hand side and right-hand side and connected to the body through subframe; the propshaft is suspended by a carryover rubber mount and connected to the body as well. Thus the electric powertrain studied is isolated by three mounts—left-hand motor mount, right-hand motor mount and propshaft mount.

Aiming at the most efficient way to improve vehicle interior noise of an electric minivan, a previous paper[7] focused at separating noise contributions from its powertrain, tires and wind using OTPA. Based on grouping of different candidate source signals, the breakdown of the synthesized signal was performed to separate and to rank individual source contributions at the driver's ear. That OTPA result under wide open throttle (WOT) condition, as illustrated in Fig. 1, concluded that wind noise started to dominate the interior noise above 5000 rpm, and the powertrain structure-borne noise was responsible for high buzzing noise at top speed. The powertrain airborne, on the other hand, dominated mainly around 3600 rpm and 1000-1400 rpm. Tire noise was transmitted mainly through structure-borne path and dominated the interior noise below 4000 rpm. Further path breakdown of the interior noise contribution into airborne and structure-borne noise, as seen in Fig. 2, reveals that all order related noise up to 1 kHz was caused by structural vibration, and the 56th motor order dominated mainly in the airborne contribution.

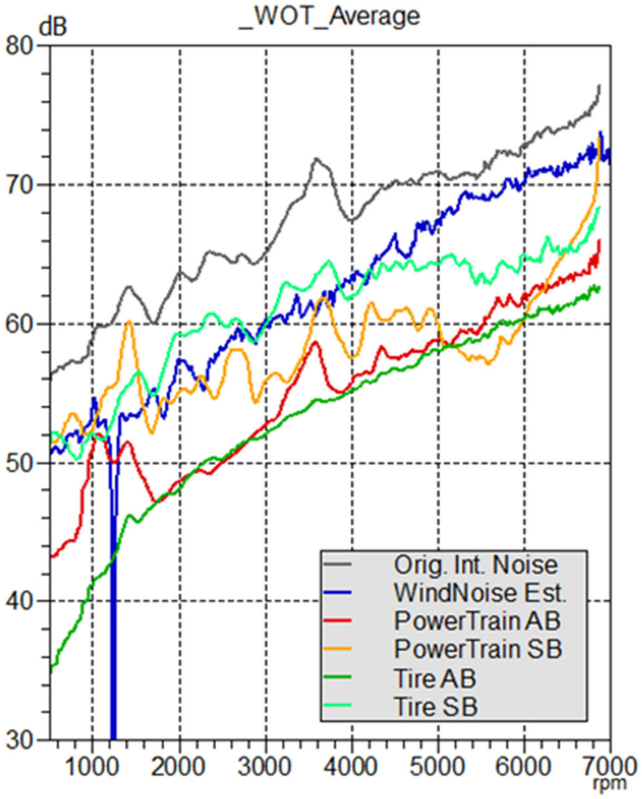


Fig. 1 – Interior noise contribution breakdown using OTPA under wide open throttle condition.

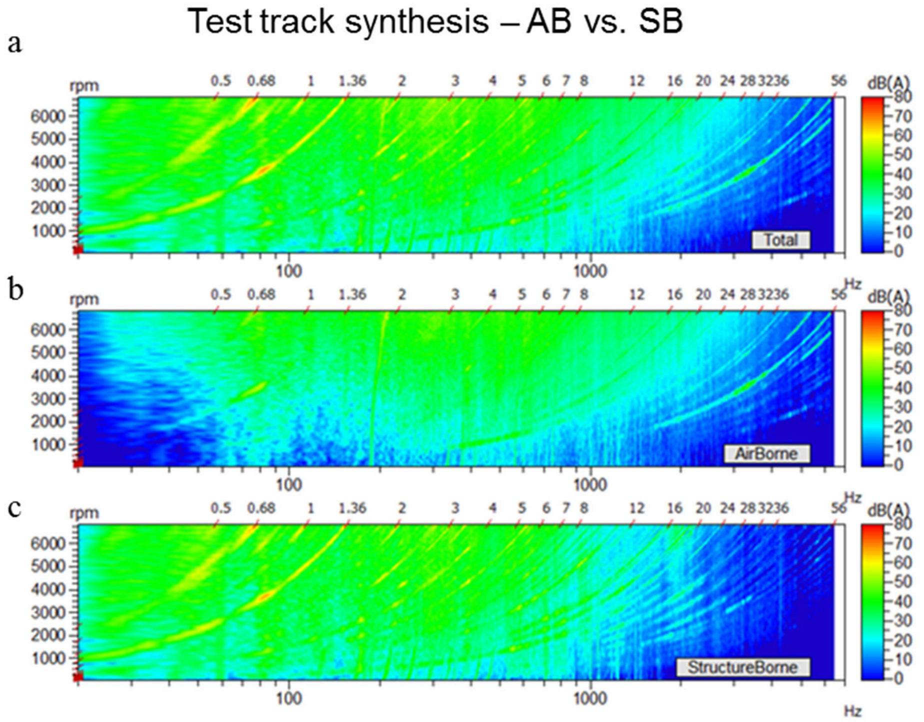


Fig. 2 –Path breakdown of the interior noise contribution into airborne and structure-born noise: (a) Interior noise total; (b) Interior airborne noise; (c) Interior structure-borne noise.

3. METHOD OF OPERATIONAL TRANSFER PATH ANALYSIS

Since powertrain mounts are attachment points of the powertrain to the body, measured vibration at the active side will contain a combination of the motor, tire and gear excitation. Such kind of locations therefore can't be used for source characterization, but could be utilized to determine which mount connection propagates most powertrain structure-borne noise in general.

Prior to undertaking the OTPA, the powertrain vibration was captured with tri-axial accelerometers at both the body side and active side of individual mount. Figure 3 shows the locations of those sensors. Four microphones, placing at driver's ears and passenger's ears, were used to acquire the perceived sound in the cabin. For the sake of simplicity, interior noise results shown in this paper were originated from the quadratic average of all four microphones; the tri-axial vibration results of each tri-axial accelerometer are quadratic averaged to one signal only. A multi-channel data acquisition frontend was used to capture all signals including motor and vehicle speeds simultaneously. To feed the OTPA algorithm, test conditions included WOT and partial open throttle (POT) on the test track.

To identify the active side excitation, mount isolation and the effect of structure-borne transfer paths on the interior noise for all three powertrain mounts, further OTPA synthesis model was built. Building models with response data on well-chosen positions as model inputs gives a good estimation of the structure-borne noise propagation in automotive applications. Following the measurements, the OTPA algorithm treats each sensor input as a unique excitation source. To mimic how the transition points add to the response, measured acceleration at the active side of left-hand motor mount, right-hand motor mount and propshaft mount played as input signals; while measured acceleration at body side of those three mounts served as output signals. The resulting transfer function matrix between inputs and outputs, processed by cross talk cancellation and singular value decomposition[6], then can be used in determining structure-borne noise contribution from the powertrain.

The information of reduction ratio of the gearbox is necessary for performing order analysis. The gearbox in the vehicle studied contains two gear pairs with 23 and 19 teeth, yielding a reduction ratio of 1.465. That is, the first order of propshaft equals 0.68th motor order.

Fig. 3 – Sensors located at the body side and active side of powertrain mounts: (a) Left-hand motor mount; (b) Right-hand motor mount; (c) Propshaft mount.

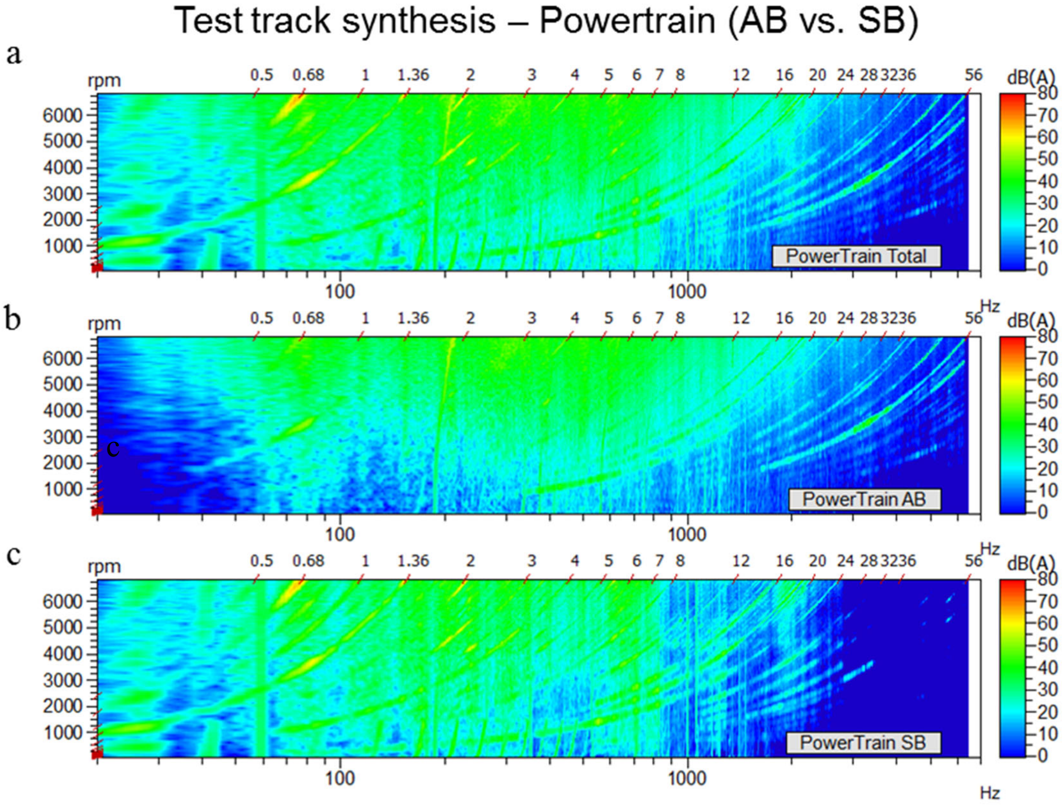
4. BREAKDOWN OF STRUCTURE-BORNE NOISE CONTRIBUTION

4.1 Powertrain Noise Breakdown

Aside from separating interior noise contributions from its powertrain, tires and wind, further breakdown of the synthesized signal can be performed to separate the path contributions at major systems. Figure 4 shows the path breakdown of the powertrain noise contribution into airborne and structure-borne noise. It is seen that the spectrum of powertrain structure-borne noise contained two noticeable orders, which related back to the first and the second propshaft orders, denoted as 0.68th and 1.36th motor orders. The results confirm that the structure-borne noise dominated the powertrain noise and the 56th motor order was transmitted by airborne. Reducing vibration through the powertrain mounts will be most effective to reduce powertrain noise.

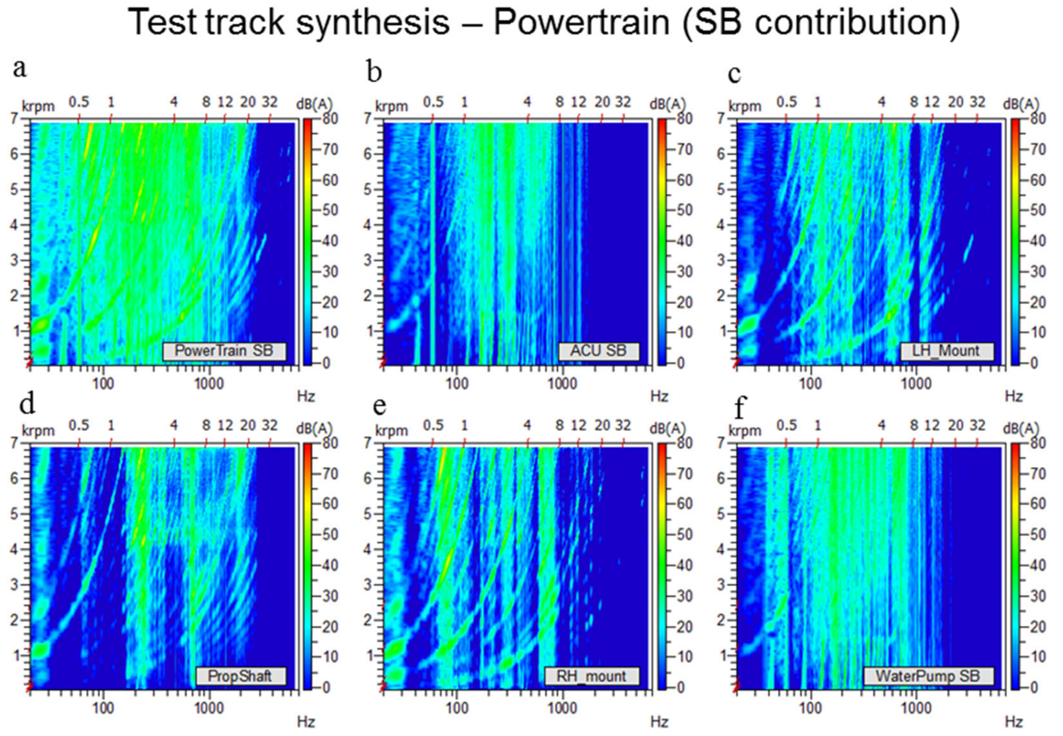
To separate the powertrain structure-borne noise contribution from different sources, further OTPA was performed. The chosen powertrain sources include the motor, the propshaft, the air conditioning unit (ACU) and the electric water pump. Figure 5 shows that the dominant orders of powertrain structure-borne noise were the propshaft related orders ranging from the first to the fourth propshaft orders, namely 0.68th, 1.36th, 2.04th and 2.72th motor orders. Closer inspection of these spectra shows that the first and the second propshaft orders, 0.68th and 1.36th motor orders, were transmitted mostly through the right-hand motor mount. By contrast, the third and the fourth propshaft orders transmitted directly through the propshaft mount. The second propshaft order transmitted through both right-hand motor mount and propshaft mount.

The propshaft first order was caused by the unbalance of the shaft. To improve the dominant first propshaft order, it would be worthwhile to balance the propshaft firstly and see how much improvement can be achieved as such. If the effect is limited, there may be a resonance problem in the powertrain. To reduce the vibration, one should therefore introduce a torsional damper between the gearbox and the propshaft first, with an option to add a damper at the differential side in a later stage.



Test track synthesis – Powertrain (AB vs. SB)

Fig. 4 – Path breakdown of the powertrain noise contribution into airborne and structure-born noise: (a) Powertrain total; (b) Powertrain airborne; (c) Powertrain structure-borne.



Test track synthesis – Powertrain (SB contribution)

Fig. 5– Powertrain structure-borne noise contribution: (a) Powertrain structure-borne total; (b) From ACU; (c) From left-hand motor mount; (d) From propshaft; (e) From right-hand motor mount; (f) From water pump.

4.2 Validation of the Mount OTPA Synthesis

To verify the mount OTPA model's accuracy, synthesis results were compared with measurement data. Based on the data measured at the body side for the three mounts, Fig. 6 shows that the mount OTPA synthesis results agreed quite well with the measured data. However, this figure does show that the propshaft synthesis did miss out on some high frequency contributions around 5 to 6 kHz.

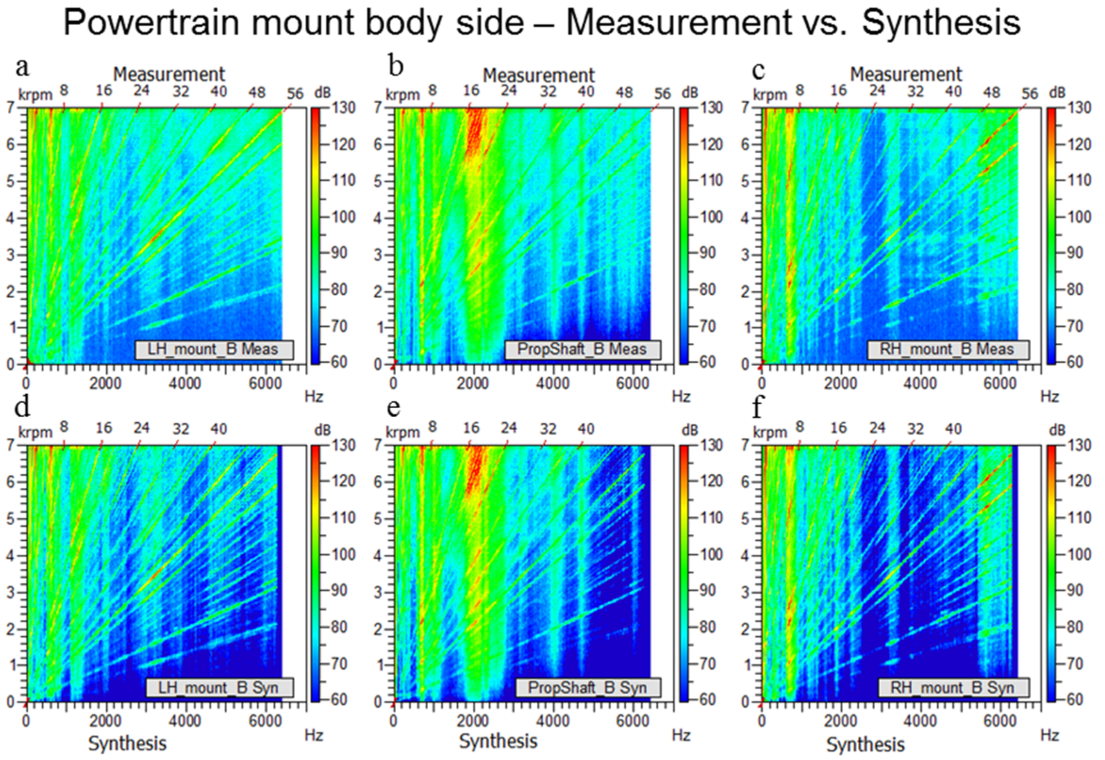


Fig. 6 – Measurement versus synthesis for the mount OTPA synthesis: (a) Left-hand motor mount - measurement; (b) Propshaft mount - measurement; (c) Right-hand motor mount - measurement; (d) Left-hand motor mount - synthesis; (e) Propshaft mount - synthesis; (f) Right-hand motor mount - synthesis.

4.3 Vibration Propagation on Powertrain Mounts

To investigate how much of the powertrain mount vibration at body side is caused by its active side vibration or due to the active side vibration of the other mounts, an OTPA focused at vibration transfer through powertrain mounts was implemented. Aiming at the mount vibration at body side, Fig. 7 shows vibration contributions from the active side of individual powertrain mounts. What stands out in these diagrams are that most of the important contributions on either the left-hand or right-hand motor mount were caused by vibration transmission through the motor mount itself. The right-hand motor mount, for instance, evidently had a resonance at 700 Hz which directly transferred through its own mount. The propshaft mount vibration at body side, on the other hand, was caused not only by its active side vibration but also by the active side vibration of the left-hand motor mount with a resonance at 2 kHz.

To address the low-frequency transmitted powertrain mount vibration, we zoomed in the contributions for 0- 400 Hz frequency range. As seen in Fig. 8, it is apparent that the third propshaft order, 2.04th motor order, was transmitted very well to the left-hand motor mount. Likewise, the first and the second propshaft orders were also transmitted well to the right-hand motor mount.

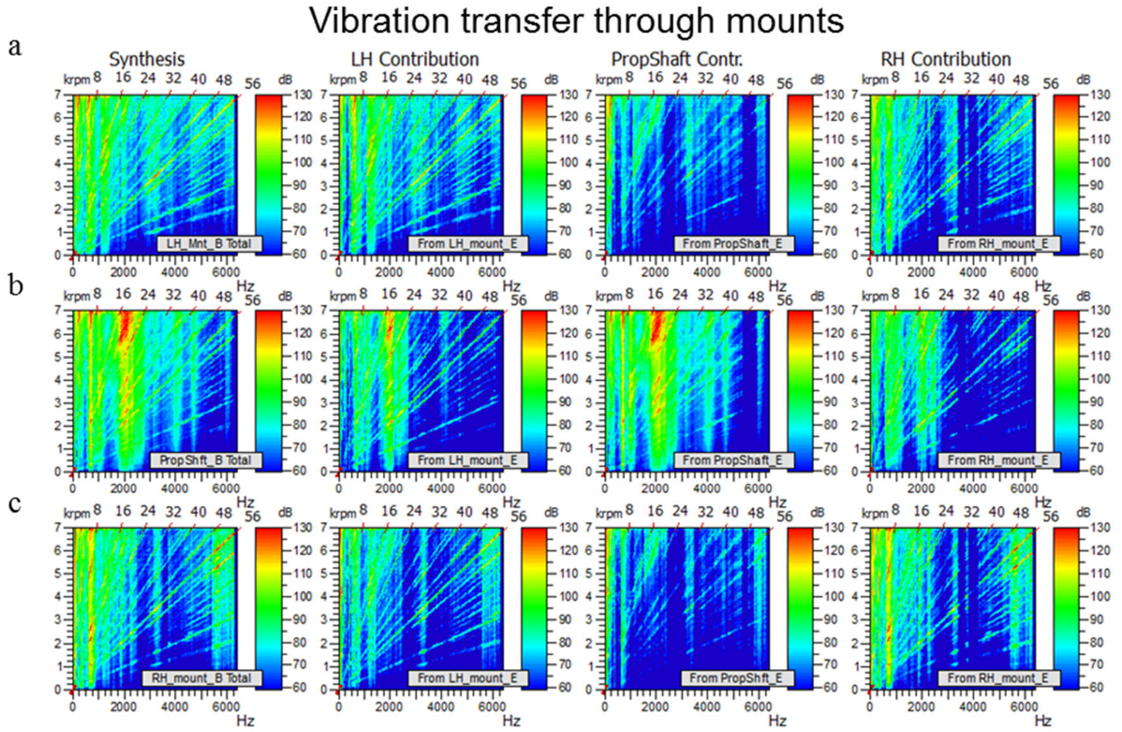


Fig. 7 – Vibration contributions from the active side of individual powertrain mounts: (a) Left-hand motor mount; (b) Propshaft mount; (c) Right-hand motor mount.

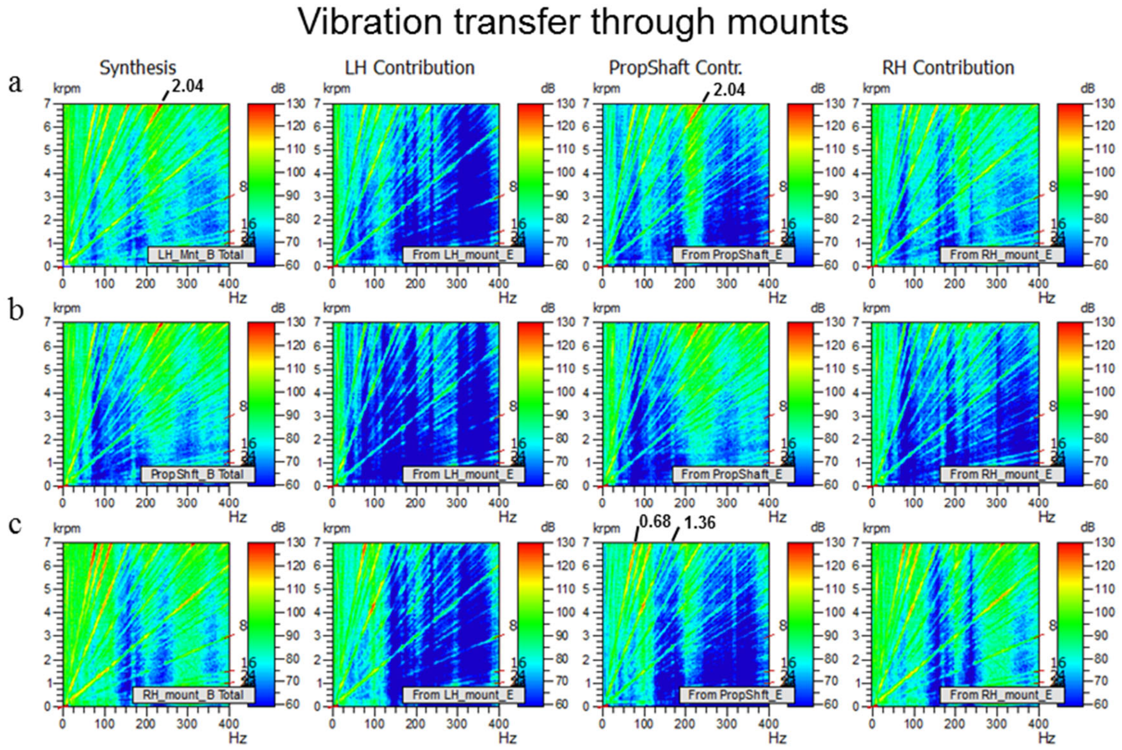


Fig. 8 – Vibration contributions from the active side of individual powertrain mounts, zoomed in for 0-400 Hz frequency range: (a) Left-hand motor mount; (b) Propshaft mount; (c) Right-hand motor mount.

In the ideal situations, the powertrain mounts should suppress vibration transmission from the motor or drivetrain to the body. If either body vibration or interior noise are sensitive to the transmitted powertrain mount vibration, the design of the mounts to achieve vibration isolation high enough, such as 20 dB, then is crucial. Based on averaged vibration spectra, Fig. 9 shows vibration contributions from the active side of individual powertrain mounts. Black and grey lines represent respectively the measurement and the synthesis, which matched quite nicely especially at higher frequencies. The figure shows furthermore that for most frequencies, vibration transmitted directly through the corresponding mount was dominant. As such, the analysis results pinpointed foremost powertrain structure-borne noise was on isolation issues of the mount itself.

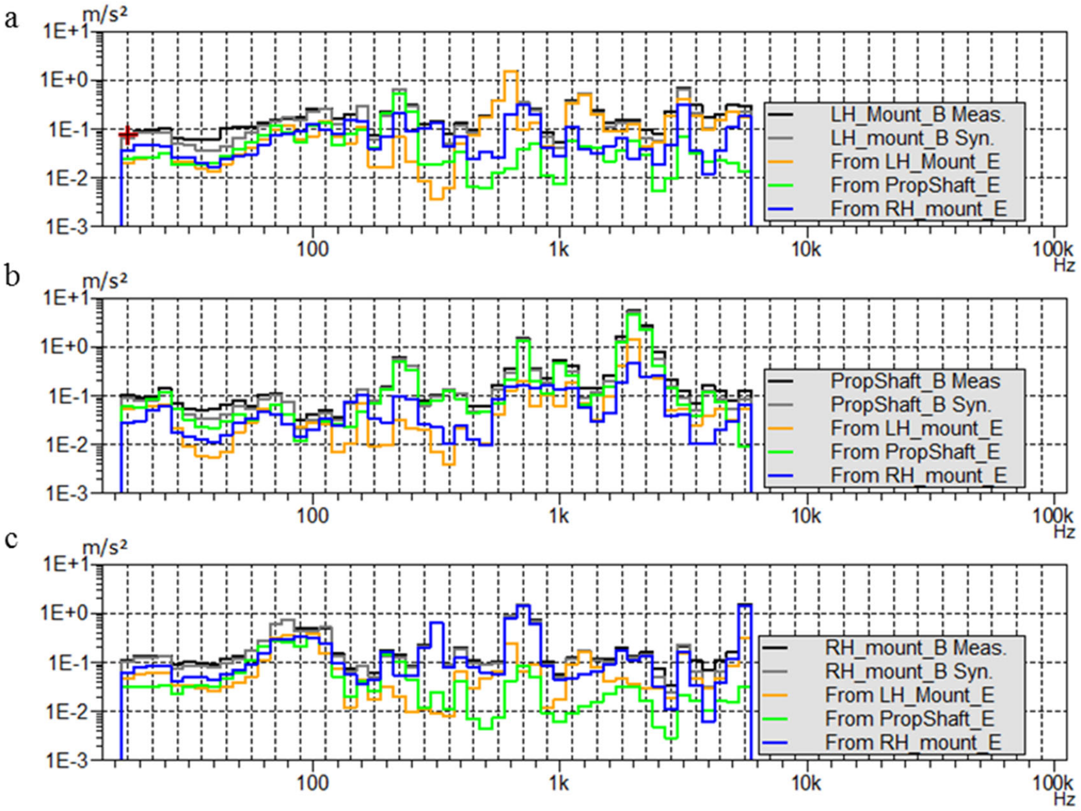


Fig. 9 – Vibration contributions from the active side of individual powertrain mounts, based on averaged vibration spectra: (a) Left-hand motor mount; (b) Propshaft mount; (c) Right-hand motor mount.

5. CONCLUSIONS

Based on our previous study of noise source separation in an electric minivan, the powertrain noise, tire structure-borne noise and wind noise were the dominant noise sources with respect to interior noise. Furthermore, all order related interior noise up to about 1 kHz was caused by structural vibration. The associated electric powertrain is isolated by three mounts—left-hand motor mount, right-hand motor mount and propshaft mount. In this study, to precisely hit the target for structure-borne noise refinement, a detailed OTPA focused at structure-borne noise propagation through powertrain mounts was carried out to examine the vibration isolation performance, especially the contribution from individual mount.

Through validated OTPA synthesis results, structure-borne noise contribution from the powertrain were further separated as contributions from the motor, the propshaft, the ACU and the water pump. OTPA analysis results show that most of the important interior noise contributions from powertrain mounts were caused by vibration transmission though the mount itself. The vibration generated at the active side of propshaft was also transmitted very well through the other mounts. Aside from the dominant vibration source from the propshaft, OTPA analysis results pinpointed foremost powertrain structure-borne noise was on isolation issues of the mount itself. Taken together, with an appropriate choice of reference and response sensors, this study strengthened that different OTPA synthesis models can be built to determine which powertrain mount propagates most structure-borne noise to a vehicle cabin with synchronized operational data only. Vibration control then can be focused and efficiently implemented to reduce the overall response level.

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