

Active Control of Structure-Borne Road Noise Based on the Separation of Front and Rear Structural Road Noise Related Dynamics

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ABSTRACT

Axle forces from tire-road interaction can excite different structural resonances of the vehicle hence a high number of sensors is required for observing and separating all the vibrations dynamics that are coherent with the cabin noise. Feed-forward road noise control strategies adopted so far rely mainly on capturing these dynamics and thus the number of sensors constitutes one major limitation of this approach.

Therefore there is a necessity for reducing the number of sensors without degrading the performance of an ANC system. In the past coherence function analysis has been found to be a useful tool for optimizing the sensor location. In this case coherence function mapping was performed between an array of vibration sensors and the headrest microphones in order to identify the locations on the structure that are highly correlated with road noise bands in the compartment.

A vehicle with an advanced suspension system was used for applying the method and defining some locations as reference signals for feed-forward active road noise control.

Three different real-time control experiments were performed with structure-borne road noise simulated by applying broad band random forces to tires through shaker transducers. A single reference feed-forward adaptive controller evaluated the signals from each sensor location with simulated road noise excitation applied to: front wheels only, rear wheels only and whole vehicle. This way it is demonstrated that the control can be focused at specific road noise bands with a low number of sensors.

CITATION: Zafeiropoulos, N., Ballatore, M., Moorhouse, A., and Mackay, A., "Active Control of Structure-Borne Road Noise Based on the Separation of Front and Rear Structural Road Noise Related Dynamics," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-2222.

INTRODUCTION

Active control of structure-borne road noise has successfully been applied to various types of vehicles with the use of multichannel feed-forward controllers [1, 2, 3, 4]. This type of control systems require a set of input signals from accelerometers. These sensors are usually placed at locations on the vehicle's structure that are highly coherent with the interior noise in the cabin. In the past a combination of accelerometer signals around the suspension system have been used, in order to improve the multiple coherence function between a set of acceleration signals and a microphone in the cabin [2, 5]. Bernhard in [2] investigated the dependency between the structural design of the suspension and the performance of an active road noise control system. ISVR and Lotus used optimization algorithms for finding the optimal sensor combination that result in the highest

reduction in the cabin [3]. Park highlighted the fact that the accelerometer number needs to be higher than the structural resonances that relate to road noise, in order to good observability of the road noise dynamics. In reality though this relates to the coherent contributions of road noise, which can be at several locations on the structure depending on the vehicle's structure. In terms of structure-borne road noise analysis measurement methods such as TPA and modal analysis can highlight the main structural paths of road noise. In this study a method that relates the road noise dynamics to the interior noise by investigating the coherence of each operational transfer path is investigated.

Currently, many modern vehicles with enhanced vehicle dynamics result in dominant acoustic road noise resonances that can be perceived by the passengers in the cabin. Road noise can be especially noticeable in vehicles with high levels of refinement, where other NVH sources are kept at very low sound pressure levels. In terms of vehicle dynamics, a multilink suspension system can introduce several road noise paths, but not all of them are significant for the interior structure-borne noise as it will be demonstrated in this study. Moreover specific vibrations from front and rear axle relate to certain noise bands and they are not identified in the current methods for sensor selection. If the separation of front and rear axle road noise and vibration is taken into account in the design of an active system, then it may result in a reasonable number of accelerometer sensors. Otherwise, a high number of accelerometers will always be a sensible solution for ensuring that the controller observes all the structural resonances that are highly correlated with road noise.

COHERENCE ANALYSIS OF VIBRO-ACOUSTIC PATHS

Road Noise Vibro-Acoustic Paths

Structure-borne road noise inside a vehicle is the superposition of sound via all the vibro-acoustic paths that contribute to the sound field in the cabin. This relates to the modal behavior of the vehicle as various structural vibrations on the vehicle structure can couple with the acoustic modes of the compartment that result to structure-borne road noise.

In [figure 1](#) the synthesis of road noise in terms of signal processing is introduced. The forces that relate to road noise are not usually measurable, but the acceleration signals on the vehicle axles are commonly recorded on the road. The measured vibrational responses are a result of the interaction of various structural paths that contribute to a measurement point on the vehicle structure.

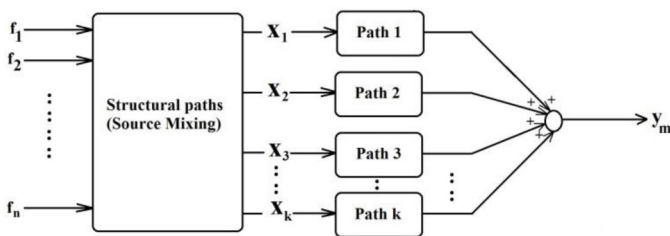


Figure 1. Signal analysis of road noise. The signals $f_1, f_2, \dots, f_n$ are n -applied forces on the axles and $x_1, x_2, \dots, x_k$ are the k -vibration responses on the vehicle structure and y_m is the road noise disturbance at a m -point inside the cabin.

In the frequency domain, the operational noise transfer paths can be defined as the ratios between each of the measured vibrational responses and the disturbance as follow

$$H_{x_k y_m}(f) = \frac{S_{x_k y_m}(f)}{S_{x_k x_k}(f)} \quad (1)$$

where $H_{x_k y_m}(f)$ are the frequency response functions between a k -accelerometer and a m -microphone. The cross-power spectrum between the sensors is $S_{x_k y_m}(f)$ and the auto-power of each of the input acceleration signal is $S_{x_k x_k}(f)$. Unfortunately, these frequency responses functions cannot be defined with operational measurements and usually experimental impact testing is used. It is important to define the coherence functions $\gamma_{x_k y_m}(f)^2$ of each operational path, since they can reveal the statistical relation between the structural and the acoustic resonances for each path.

$$\gamma_{x_k y_m}(f)^2 = \frac{|S_{x_k y_m}(f)|^2}{S_{x_k x_k}(f) S_{y_m y_m}(f)} \quad (2)$$

In [figure 1](#) it can be noticed that the vibrational energy that is input by the tire-road force onto vehicle body is diffused through the multiple structural paths. As a result the measured vibrational signals on the road are the summation of the multiple structural contributions of each structural path from the tire to the suspension or subframe. As a result, the structural responses at each axle are partially correlated.

A solution to this problem is to create a set of uncorrelated acceleration signals. This can be done by decomposing the power spectra of the acceleration matrix with the use of SVD (SVD) in order to identify the main Principal Components (PC) of road noise [7]. The drawback of Principal Component Analysis (PCA) is that it de-correlates and ranks the structural sources, but it does not provide an insight into the location of the structural source [1].

As a result, a series of vibro-acoustic methods such Transfer Path Analysis are usually applied on a vehicle in order to locate the structural road noise resonances and the main paths of road noise.

In [equation \(1\)](#) the accelerometer and microphone signals may show some coherence if the accelerometer is placed close to, or at a structural road noise resonance. This implies that there is enough structural energy at some specific accelerometer locations, where low frequency road noise dynamics dominate.

In the following section this phenomenon is demonstrated by calculating the coherence between each accelerometer and microphone sensor in the cabin, in order to create a map of the coherence of the whole vehicle.

The highest contributing paths of road noise can be identified and used later as inputs to a feed-forward ARNC system. As a second step of the proposed method the virtual coherence [6, 7] is used for calculating the summed coherence of the decomposed acceleration signals. The acceleration cross-power spectral density (CPSD) matrix can be decomposed as follow [7]

$$S_{x_k x_k}(f) = U(f) S_{v_k v_k}(f) V(f) \quad (3)$$