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IDENTIFICATION OF VEHICLE INTERIOR NOISE SOURCES USING VIBRO-ACOUSTIC SPECTRAL ANALYSIS METHOD

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Abstract

Continuous exposure to sound emitted by road vehicles will have direct effect on the comfort and fitness of the drivers, especially during long distance travel. It is imperative that automotive manufacturers invest a lot of effort and money to improve and enhance the vibro-acoustics performance of their product. The enhancement effort would be very difficult and time consuming if one relies only on ‘trial and error’ methods without prior knowledge about the sources itself. Complex interior noise inside the vehicle cabin originated from various sources and travel through many pathways. It is vital for the automotive engineers to identify the dominant noise sources from measurement data obtained inside the vehicles such as tyre noise, engine noise, exhaust noise and noise due to turbulence. In this paper, a multi-channel analyzer is utilised to measure and record vibro-acoustic signals. Computational algorithms are also employed to identify contribution of the various sources towards the measured signals. These achievements can be utilised to detect, control and optimise interior noise performance of road transport vehicles.

1. INTRODUCTION

Sound and vibration quality of road vehicles play a major role to provide quite and comfortable rides [1]. Automotive companies have invested a lot over last decades to achieve this goal and attract the customer demands. The sound and vibration quality refinement consists of dissipation of unwanted noise at three stages; source, transfer path and receiver. The first one is the subject of this paper; finding the sources of noise in a passenger vehicle compartment. Typically engineers use two standard methods for noise path analysis and finding the contribution of sources to overall response [2], [3].These methods are commonly similar; based on the total received sound pressure level or vibration as the superposition of partial results which describe the contribution of each transfer path. User should only choose between the ‘force vector method’ and ‘full matrix method’. The problem with these methods is that the source should be disconnected from the receiver so extra time and cost should be allocated.

Spectral analysis methods have this advantage that user don't need to make the disconnection between the sources and receivers. In this paper, the Conditioned Spectral Analysis (CSA) and Virtual Source Analysis (VSA) are used to identify the vibro-acoustical sources of noise emitted inside the vehicle compartment.

1.1 Conditioned spectral analysis (CSA)

Conditioned Spectral Analysis (CSA) is based on coherence methods used by engineers to find the contribution of each source to the overall response in a multiple input- multiple output system [4], [5]. This method has become popular in automotive applications [6]. The coherence function is an indication of linear relationship between the input (x) and output (y) of a system. Multiplication of the ordinary coherence function $\gamma^2{}_{xy}$ with the measured output spectrum, the coherent output power (COP) spectrum is calculated as shown in Eq. (1). It is a measure of the amount of the output power which linearly related to the input.

$$\gamma^2{}_{xy}(f)G_{yy}(f) = \frac{\left|G_{xy}(f)\right|^2}{G_{xx}(f)} \tag{1}$$

Where $G_{xx}(f)$ and $G_{yy}(f)$ are autocorrelations of channel x and channel y respectively and $G_{xy}(f)$ is the cross correlation between them.

In a multiple input-single output (MISO) system that inputs have some correlations, the output power spectrum could not show the true amount of the output power linearly related to one of the inputs because the coherence function is already affected by other inputs due to their correlations. This is one of the main interests in automotive applications such as correlation between vibration signals measured from different engine mounts of a vehicle. The need for CSA rises at this point as a tool to remove the linear effects of other inputs from the problem. For example consider X_1 and X_2 as two correlated inputs. The conditioned signal 2 from signal 1; $X_{2.1}$ can be obtained by using Eq. (2):

$$X_{2.1} = X_2 - L_{12}X_1 \tag{2}$$

Here L_{12} is the frequency response function between the two signals. After conditioning the correlated inputs in a MISO system, contribution of each of the inputs can be calculated. First step of conditioning in such a system is to rank the sources. One method of ranking is to check the causality between signals [7]. In this approach, Hilbert transform method is used to determine the priorities of the inputs in frequency domain. Hilbert transform pairness of real and imaginary parts of the frequency response function (FRF) is necessary and sufficient for a linear system consisting of two signals to be causal or the input signal is prior to the output signal [8]. Let's assume $R(\omega)$ and $I(\omega)$ as real and imaginary parts of the FRF of a linear system. They need to satisfy the Hilbert transform pairness as indicated in Eqs. (3) and (4) [9]:

$$R(\omega_0) = -\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{I(\omega)}{\omega-\omega_0}\,d\omega \tag{3}$$

$$I(\omega_0) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{R(\omega)}{\omega - \omega_0} d\omega \tag{4}$$

First of all the ordinary coherence function between the pair of inputs should be checked to make sure that their coherency is significant over the predetermined frequency band. Next, the pairness of real and imaginary parts of the two FRFs (e.g. $H_{ij}(jw)$ and $H_{ji}(jw)$) will be checked. If $H_{ij}(jw)$ satisfies Eqs. (3) and (4) then $X_i(\omega)$ should have caused $X_j(\omega)$ and vice versa. This causality approach is used in this paper to define the rank of the sources prior to start signal conditioning. The cross-spectral matrix of inputs is constructed to facilitate the signal conditioning in a MISO system. The method to construct this matrix is mentioned in the next part.

1.2 Virtual source analysis (VSA)

This approach is a tool to find the number of incoherent sources in a multiple input system [6]. Basic of this method is to make the cross-spectral matrix of inputs and apply the singular value decomposition method (SVD) to find the non-negligible eigenvalues. The numbers of non-negligible eigenvalues correspond to the number of incoherent sources in the system. The cross-spectral matrix made by auto and cross-spectrum functions of p input channels is shown in Eq. (5):

$$[S(f)] = \begin{bmatrix} S_{11} & S_{12} & . & . & S_{1p} \\ S_{21} & S_{22} & . & . & S_{2p} \\ . & . & . & . & . \\ . & . & . & . & . \\ S_{p1} & S_{p2} & . & . & S_{pp} \end{bmatrix} \tag{5}$$

Where elements on the main diagonal of $[S(f)]$ are auto-spectrum and the rest are cross-spectrum functions of input channels (all are frequency dependent). After performing the SVD method, the non-negligible (virtual) sources are calculated as shown in Eq. (6). Virtual sources are incoherent phenomena extracted from the physical sources using the SVD approach and their number is equal to the number of non-negligible eigenvalues of the cross-spectral matrix of the input signals. Here $[X]_{pk}$ is the matrix of virtual sources, $[U]_{pk}$ is the matrix of left eigenvectors and $[\sigma]_{kk}$ is a diagonal matrix which elements of its main diagonal are square roots of the corresponding *k* non-negligible eigenvalues:

$$[X]_{pk} = [U]_{pk} [\sigma]_{kk} \tag{6}$$

Contribution of virtual sources to each channel can be found from this matrix. Virtual coherence (signature) of each virtual source shows the contribution of each input channel to that source. It is computed by dividing the contribution of a virtual source by the auto-spectrum of the corresponding input channel. By comparing the signatures of virtual sources and their contribution to the response channel, contributions of each input channel to the response is calculated.

Contrary to the CSA approach, in this method there is no requirement to rank the sources and can be considered faster and easier to use. Nowadays, it is broadly used in direct and inverse source identification studies [10].

2. METHODOLOGY

The main objective of this paper is to identify the sources of noise emissions inside a passenger compartment of a stationary vehicle. This sound can be considered as a stationary random signal which originated from different airborne and structure borne sources. Fig. 1 shows an example of this noise measured inside the vehicle compartment in the frequency span of 1 KHz. Because of its stationary nature, it can be roughly predicted using linear regression analysis. For example, the COP function between the engine sound and interior can be calculated using Eq. (1):

$$COP(f)_{engine.interior} = \gamma^2(f)_{engine.interior} . G(f)_{interior.interior} \tag{7}$$

As it mentioned before, the COP function defines a linear relationship between the input and the output of the system. Then a linear function can be derived by measurement of the engine and interior sounds and calculation of the COP function between them. To establish a reliable formula for future prediction, it's feasible to use many of these data sets in a linear regression analysis recorded at special engine revolution speed and frequency. Two kinds of errors should be notified here. The first one rises due to non-linearity of the system which corresponds to the non-coherent output power spectra (NCOP). It is needed to perform also non-linear regression analysis to count these non-linearities and the output channel will be the summation of both COP and NCOP functions. Second error is due to the coherency between noise sources. For example the coherence function between engine and interior also has some contribution from other sources rather than engine itself. This kind of error can be eliminated by using the partial coherency function after performing the CSA method.

First of all these points are considered as potential sources of noise emissions:

- Engine sound
- Exhaust sound
- Vibration of engine components

Bruel & Kjaer instrumentation series, namely; portable and multi-channel PULSE type 3560D with Head and Torso (HAT) type 4100, triaxial accelerometers type 4506B and prepolarized free-field ½ " microphones type 4189 were utilised in the measurement devices. The B & K Pulse Labshop is the measurement software and all microphones are calibrated with the B & K calibrator type 4231 at 1 KHz and 94 db level. Test vehicle is Proton Perdana with neutral gear and recordings were carried out at closed windows and air conditioning system off.

One triaxial accelerometer is connected to each engine mount to measure the vibration signals in three directions (x axis toward the ground and y axis facing the driver compartment). Position of microphones used for engine and exhaust sound measurements follows the ISO 5130 which established for measurements of noise emitted by stationary road vehicles [11]. For engine sound measurement, the height of the free-field microphone above the ground is 0.5 m and its reference axis for free field conditions is parallel to the ground and mounted in vertical plane through the front axel at a distance of 0.5 m (engine is in the front). It is located at the opposite side related to the driver seat and the engine hood is open. For the exhaust sound measurements, a microphone is pointed towards the outlet orifice and located at a distance of 0.5 m. It is situated parallel to the ground at an angle of 45º ± 10º with the vertical plane in-line with direction of the gas flow. The HAT placed at the driver position to record the interior noise as the response channel. Experiment is performed at constant 4000rpm engine revolution and signals are acquired simultaneously.

3. RESULTS AND OBSERVATIONS

After performing the experiment, the CSA and VSA methods used for post processing of the recorded signals. It has the advantage of finding the adequacy of each method and comparing them to evaluate the validity of results.

3.1 Post processing by CSA method

A schematic of the CSA approach is shown in Fig. 2. After recording the source signals, first step is to find the ranking of sources using the Hilbert transform approach. By implementing the Eqs. (3) and (4) or using plot, the Hilbert transform pairness between real and imaginary parts of FRFs for all two pairs of source signal are checked. For example if consider x and y as two different source signals the pairs will be $H_{xy}(f)$ and $H_{yx}(f)$. Fig. 3 and 4 show examples of this calculation over a frequency band of 1 KHz. Causality can be found very easily by looking at the plots. Until 200 Hz, the two curves of $H_{xy}(f)$ match each other very well while those of $H_{yx}(f)$ have different phases. Above 200 Hz to 1 KHz, the curves of $H_{yx}(f)$ mach each other very well. It means that in the frequency range of 0-200 Hz, signal x is prior to signal y and in the frequency range of 200 Hz-1 KHz signal y has priority in relation with signal x. The vital part of priority checking accomplished and sources were ranked before signal conditioning. Signals were conditioned stage by stage and the coherent output powers of the conditioned sources are calculated. Three strong sources are shown in Figs. 5 to 7. At each plot, the solid line is the sound pressure level (SPL) of the recorded interior (response) channel. The dashed line shows the amount of linear relationship between the corresponding source and interior. Then these plots show that how much of the interior noise is linearly related to these sources. The strong peaks of the interior noise less than 200 Hz are all harmonics of the half engine speed. They are originated from the vibration of the engine structure transmitting through the engine mounts (structure borne noises). Fig. 5 is an example which shows that these noises are linearly related to the Z axis of the right engine mount (toward the vehicle left side from the driver view). Vibrations from engine mounts are highly correlated and nearly have the same pattern. After 200 Hz, other harmonics are also added and the main source is the engine sound recorded by microphone (airborne) as shown in Fig. 6. Contributions from the exhaust noise are plotted in Fig. 7. It has perfect linear relationship at some of the half engine speed harmonics, for example 230 Hz, 560 Hz and 730 Hz.

3.2 Post processing by VSA method

By using Eqs. (5) and (6), the cross-spectral matrix computed and the SVD method applied on the frequency span of 200 Hz, only the first virtual source had significant contribution. Signatures computed in the form of matrices that each line related to the virtual coherency between one channel and the corresponding virtual source. Some of them are shown in Fig. 8. The horizontal axis is frequency and the vertical axis includes the sources. The colorbar on the right side of the plot shows the amount of coherency between the physical sources and the corresponding virtual source (virtual coherence). This plot indicates that the engine mount vibration signals are dominant and highly coherent in this frequency band. Engine and exhaust sounds also have their own contributions at the harmonics of the half engine speed but they are not as strong as the structure borne sources.

4. CONCLUSIONS

Spectral analysis methods carried out to find the vibro-acoustic sources of the noise inside a vehicle compartment. The CSA and VSA approaches were shown to be adequate to achieve this goal. Source ranking is vital before starting the CSA, which utilised Hilbert transform method to do the ranking. The coherent output powers of the conditioned sources explained that in the frequency span of 200 Hz, the structure borne sources are dominant. Although, noise from the engine and exhaust have their own contribution but weaker and only at the harmonics of the half engine speed (combustion noise). VSA method carried out in this study is much faster and approves the previous results. The virtual coherence (signature) matrices are appropriate tools to find the contribution of each channel to the corresponding virtual sources. Studying of the signatures of the significant virtual source gives the same results as before. It shows that the structure borne sources are dominant, also it is clear that they are highly coherent in this area.

REFERENCES

[1] M. Jailani M. Nor., H. Nahvi and M. Hosseini Fouladi, "Evaluation of acoustical and vibration comfort indicators inside a passenger car", *Proceedings of the 8th international symposium of transport, noise and vibration*, St. Petersburg, Russia, (2006).

[2] LMS International, "Transfer path analysis, the qualification and quantification of vibro-acoustic transfer paths", (1998).

[3] MSX International, "I-DEAS noise path analysis", MTS System Corporation, (1998).

[4] A.G. Piersol, "Use of coherence and phase data between two receivers in evaluation of noise environments", *J. Sound Vib.*, **56**(2), 215-228, (1978).

[5] J.S. Bendat and A.G. Piersol, "*Engineering application of correlation and spectral analysis*", Wiley Interscience, (1980).

[6] Q. Leclere, C. Pezerat, B. Laulagnet and L. Polac, "Application of multi-channel spectral analysis to identify the source of a noise amplitude modulation in a diesel engine operating at idle", *Applied Acoustics*, **66**, 779-798, (2005).

[7] B.K. Bae and K.J. Kim, "A Hilbert transform approach in source identification via multiple-input single-output modeling for correlated inputs", *Mechanical Systems and Signal Processing*, **12**(4), 501-513, (1998).

[8] A. Papoulis, "*The Fourier integral and its applications*", McGraw Hill, (1962).

[9] G.R. Tomlinson, "Developments in the use of the Hilbert transform for detecting and quantifying non-linearity associated with frequency response functions", *Mechanical Systems and Signal Processing*, **1**, 151-171, (1987).

[10] Q. Leclere, "Etude et Developpement de la Mesure Indirecte d'Efforts-Application a`l'Identification des Sources Internes d'un Moteur Diesel", Ph.D. Thesis, INSA Lyon, (2003).

[11] International Organization for Standardization, ISO 5130, "Measurement of noise emitted by stationary road vehicles-survey method", (1982).

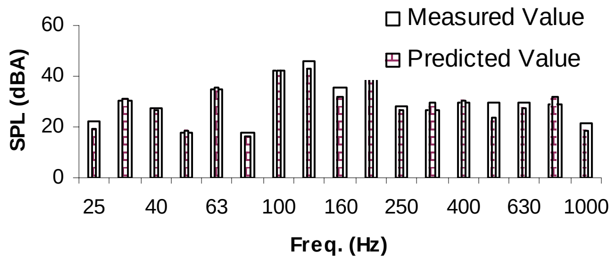

Figure 1. Noise emission inside of a stationary vehicle at 1/3 octave bands, 2000rpm

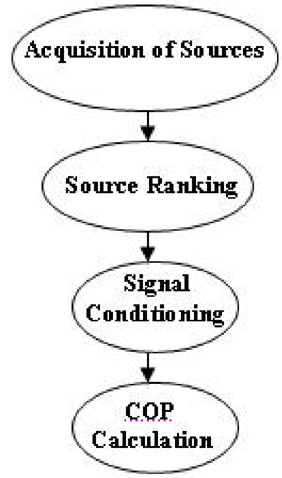

Figure 2. Schematic of the CSA approach.

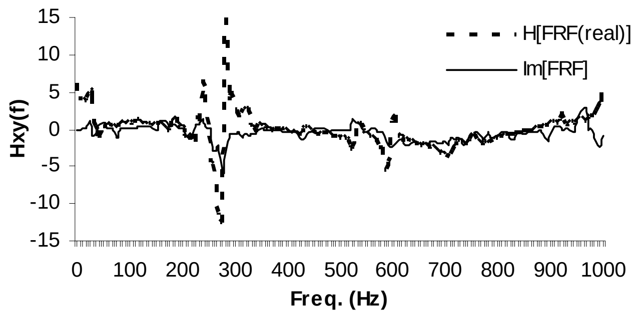

Figure 3. Imaginary Part and Hilbert transform of the real part of the FRF between x and y axis signals of one engine mount; $H_{xy}(f)$.

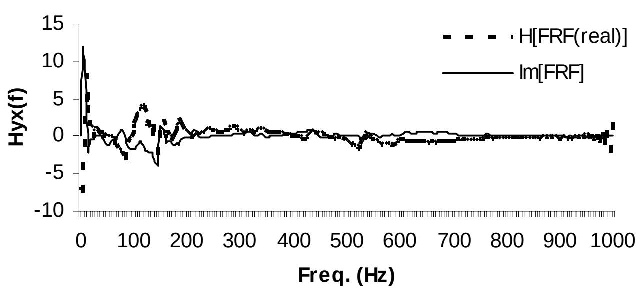

Figure 4. Imaginary Part and Hilbert transform of the real part of the FRF between y and x axis signals of one engine mount; $H_{yx}(f)$.

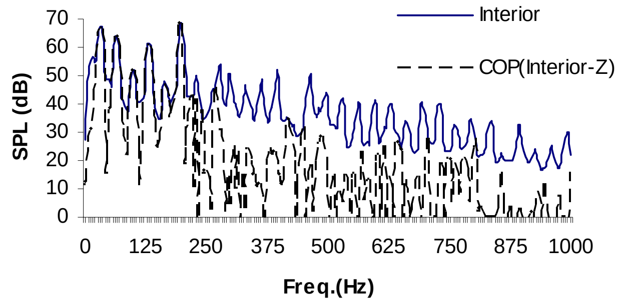

Figure 5. Diagrams of the interior noise and coherent output power between the interior and Z axis signal of the right engine mount.

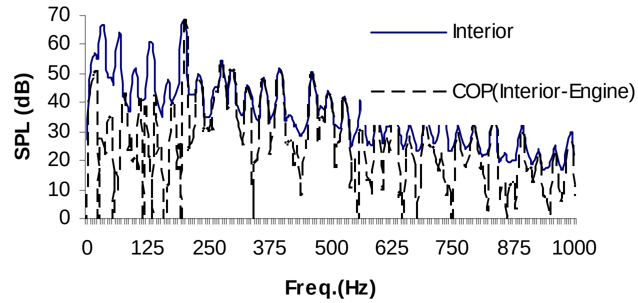

Figure 6. Diagrams of the interior noise and coherent output power between the interior and the engine sound.

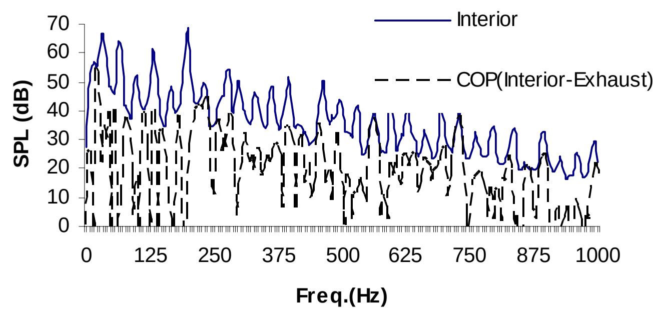

Figure 7. Diagrams of the interior noise and coherent output power between the interior and the exhaust sound.

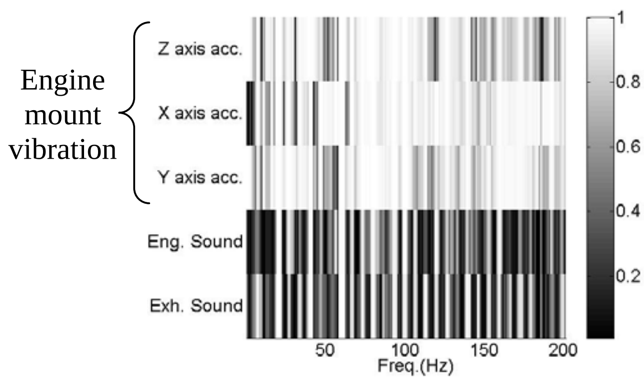

Figure 8. Signature (virtual coherences) of the first virtual source for the x, y, z axis of left engine mount, engine and exhaust sound.