Structural Dynamic Applications Using Principal Component Analysis Method

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Abstract. Principal component analysis (PCA) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. The PCA method enables to reduce the study of a complex noise and vibration problem, with multiple partially correlated references, to the study of independent, uncorrelated problems. This paper describes systematic processes for road noise improvement along with measurement and analysis process. The noise sources are identified by using a source decomposition method. In the next step the main noise paths are identified by using a transfer path analysis method (TPA). Based on obtained results, the design modification of body panels is suggested for road noise reduction by using a panel contribution analysis. Finally the method will be applied to road noise reduction process for a new vehicle.

Keywords: Noise reduction · Transfer Path Analysis (TPA) · Principal Component Analysis (PCA) · Panel contribution

1 Introduction

In the past decade the needs of the automotive industry have changed due to economic and ecological reasons. The development cycles have become shorter and more cost sensitive. The interior noise and vibration characteristics (NVH) of vehicles have become important factors in influencing customers' options. Many engineering tools have been developed for analyzing and optimizing vehicle NVH. An important group is represented by the transfer path analysis methods (TPA). The purpose of these methods is to analyze the noise transfer between noise sources and a receiver [1]. For example, the engine in a car is a noise and vibration source and the driver or another passenger is the receiver. Knowing the noise source, there are many connections and possible paths through which noise and vibration energy can arrive at the receiver. Using TPA the critical loads and propagation paths can be identified.

The solutions for improving the road induced interior noise problems on driving also are based on TPA. The source of road noise comes from contact between tire and

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road surface, but the most important transfer paths depend on components and coupling elements. In the first step this paper first identifies contribution of structure borne noise to interior noise from tire. Secondly, the contribution of the body panels to interior noise is characterized. Finally, the body panel improvements are discussed. These steps are applied to a new passenger car development process.

2 Deterministic Versus Random Loads

Deterministic Data. It is said about these data that are deterministic when both the excitations and the responses are described by deterministic frequency spectra. A representative example of deterministic data is the engine noise, Fig. 1. If it is considered that the car is excited only by the engine, the excitation/response relation is related to a single phenomenon, the engine turning. This means that measured crosspower data can be converted into frequency spectra reported to the engine signal. One reference will clarify all the responses. The Transfer Path Analysis will use the reference spectra as input loads.

Random or Stochastic Data. Atypical example it is represented by the vibrations generated in the car by the road inputs, Fig. 2. The crosspowers and autopowers contain information regarding the correlation between excitation and response signal with respect to other excitations/responses and itself. The input signals are correlated and one needs a randomization approach to estimate the degree of correlation between them. This indicates that it needs more than one independent source to explain all the responses.

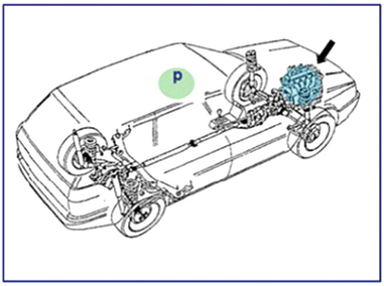

Fig. 1. Engine noise and vibration as deterministic excitation

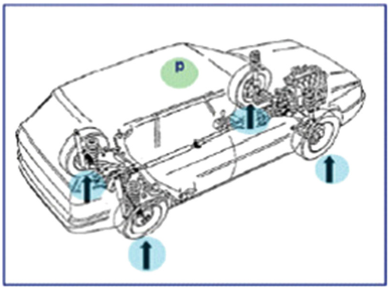

Fig. 2. Random vibration caused by the road input

Multiple References without Correlation. When multiple phenomena are acting, it is needed to consider more references to create the referenced spectra of the excitations for each reference. If there are two references, *ref*_1 and *ref*_2, and an excitation signal, *excit1*, than the crosspower matrix is given by:

$$\begin{bmatrix} ref\_1 * ref\_1 & ref\_1 * ref\_2 & ref\_1 * excit\_1 \\ ref\_2 * ref\_1 & ref\_2 * ref\_2 & ref\_2 * excit\_1 \\ excit\_1 * ref\_1 & excit\_1 * ref\_2 & excit\_1 * excit\_1 \end{bmatrix} \quad (1)$$

The values $ref\_2 * ref\_1$ and $ref\_1 * ref\_2$ evaluate the coherence between the reference signals. If they are zero, there is no correlation between them and it is sufficient to create the referenced spectra for *excit1*, with each reference. The forced response is calculated with each of the spectra and sums the two responses to obtain the total response. The addition is carried out using an energetic formulation as shown below:

$$(output)^2 = (output\_1)^2 + (output\_2)^2 \quad (2)$$

Multiple References with Partial Correlation. When the references are partially correlated, it is necessary to calculate multiple referenced spectra. Following the procedure mentioned above to compute the responses would result in overestimating the output, because each of the two referenced spectra does not only contain the information related to one reference. As the reference is correlated to another reference, it results the non-zero values $ref\_2 * ref\_1$ and $ref\_1 * ref\_2$ for the matrix shown above. The Principal Component Analysis can solve this.

3 Road Noise Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) allows reducing the study of a complex noise and vibration problem with multiple partially correlated references, to the study of independent, uncorrelated problems. The PCA splits the non-coherent vibrations into coherent sets of vibrations and assigns the latter to the 'virtual' sources that can be treated in a similar way to coherent sources. Singular Value Decomposition (SVD) techniques are applied on a multi-reference crosspower matrix. The crosspower matrix is decomposed into its principal components, which gives as many single reference sets of crosspowers as there are references. These new sets of references are called principal components. The PCA process is shown in Fig. 3.

The references are the measurement locations, representative for the phenomena that make the structure's dynamic behaviour. The responses, or slave measurements, are the measurement locations which are not used as references. They describe the dynamic response as it is observed by the operator of the vehicle under test. The reference signals are in general partially correlated to each other. An uncorrelated set of principal component spectra can be obtained by using a principal component decomposition of this reference set.

Virtual Crosspower Spectra. With the multi-reference crosspower averaging, data is condensed into the following two matrices:

- the autopower matrix $\lfloor S_{X,X} \rfloor$ of the references;
- the crosspower matrix $\lfloor S_{Y,X} \rfloor$ of the responses with respect to these references.

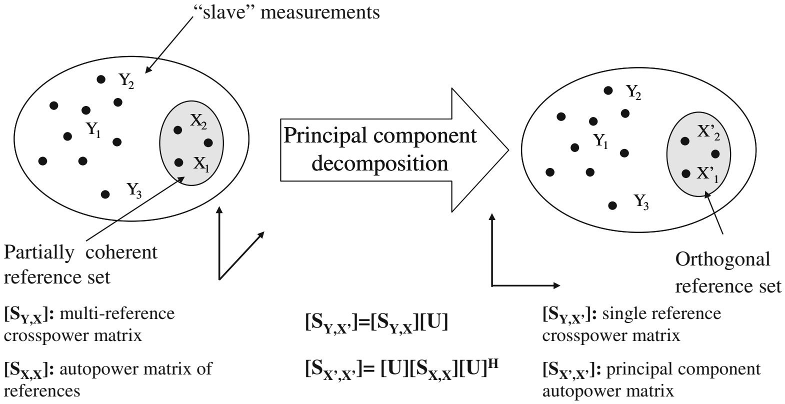

Fig. 3. Principal component analysis process

The reference autopower matrix $\lfloor S_{X,X} \rfloor$ is decomposed by the eigenvalue decomposition into its orthogonal, independent or principal component autopower matrix $\lfloor S_{X',X'} \rfloor$, the so-called virtual reference autopower:

$$\left[S_{X,X}\right] = [U]\left[S_{X',X'}\right][U]^H \tag{3}$$

The matrix $[U]$ is the unitary eigenvector matrix, and $[U]^H$ is its Hermitian transpose. The principal component autopower matrix $\lfloor S_{X',X'} \rfloor$ is a diagonal eigenvalue matrix, the principal components being orthogonal with respect to each other. It represents the new orthogonal reference set, or the set of virtual independent references. The elements of this diagonal are $S_{ii}(i = 1, nref)$.

The crosspower matrix $\lfloor S_{Y,X} \rfloor$ can be transformed to a set of crosspowers with respect to this new orthogonal virtual reference set. This gives:

$$\lfloor S_{Y,X'} \rfloor = \lfloor S_{Y,X} \rfloor [U] \tag{4}$$

The matrix $\lfloor S_{Y,X'} \rfloor$ contains the virtual crosspower spectra, which are "single reference" crosspowers, with respect to the virtual orthogonal references (principal components). The elements of this matrix contain for a response *j* and a virtual reference *i'*, $S_{ji'}$.

Referenced Virtual Spectra. From the virtual crosspowers, the referenced virtual spectra can be derived. This is finished by dividing the single reference virtual crosspowers by the square root of the autopowers of each of the principal components. These referenced spectra are to be used as input data to the Transfer Path Analysis (TPA). For a response *j* and a virtual reference *i'*, the referenced virtual spectrum is calculated as: $S_{ji'} \Big/ \sqrt{S_{i'i'}}$. The outcome of PCA consists of *n* sets of the referenced virtual spectra, *n* being the number of references chosen in the PCA.

Referring to the principal component autopowers, the following observations can be made:

- the singular values σ_i are the autopowers of the virtual references or the principal component autopowers;
- the virtual references *X'* are uncorrelated (diagonal matrix);
- principal component autopowers are sorted: $\sigma_1 > \sigma_2 > \ldots > \sigma_n$ and offer an indication of number of independent active phenomena that build up the structure's dynamic behaviour.

The referenced virtual spectra are used as the operational data for the transfer path analysis model. The different virtual spectra related to the different independent sources are considered as individual load cases, which can be processed in sequence.

4 Road Noise Reduction Using Source Decomposition and Panel Contribution Analysis

4.1 Road Load Source Decomposition Process

The interior noise in automobiles is generally classified into airborne and structure borne noise. The structure borne noise is influenced by the mount characteristics and vehicle structure dynamics. The powertrain inputs and road inputs are the major contributors to the structure borne sound problem [2–6].

First application of this study includes two purposes [7]:

- To find out the principal components (virtual references) those contribute to the complex noise and vibration problems in order to reduce them;
- To compute the non-coherent steering wheel vibrations caused by the road load inputs in the time domain, which are applied at four tire patch excitation points.

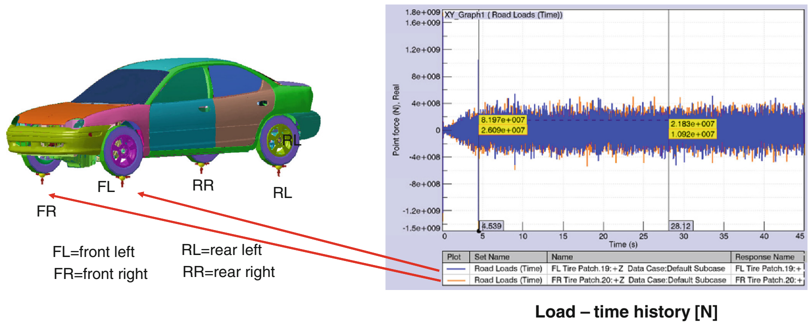

Fig. 4. Car model, tire patches and load time history

The load application points are the tire patches, where the large masses are attached, Fig. 4. The interface points are the subframe and steering system points and the response points are the steering wheel points.

The history loads contain the measured road load time data. These are derived from a road profile measurement, which contains two random signals, one for the front-left (FL) tire and one for the front-right (FR) tire in the Z-direction. For the rear tires the loads in the time domain are the same, but they are delayed with some time. The forces are high in amplitude as they were pre-processed to apply to a model with large masses attached to the tire patches. These road loads are coming from a test database.

In the next step a crosspower set of the road loads is calculated. The crosspower set handles crosspowers and autopowers. Crosspowers describe the spectral contents of the part of a response signal that is correlated to a reference signal, whereas principal components that relation between a response signal and a virtual reference signal. The crosspower set will be used for road noise principal analysis case.

In Fig. 5 it is shown the total displacement of one point of the steering wheel as an output response to the virtual reference spectra.

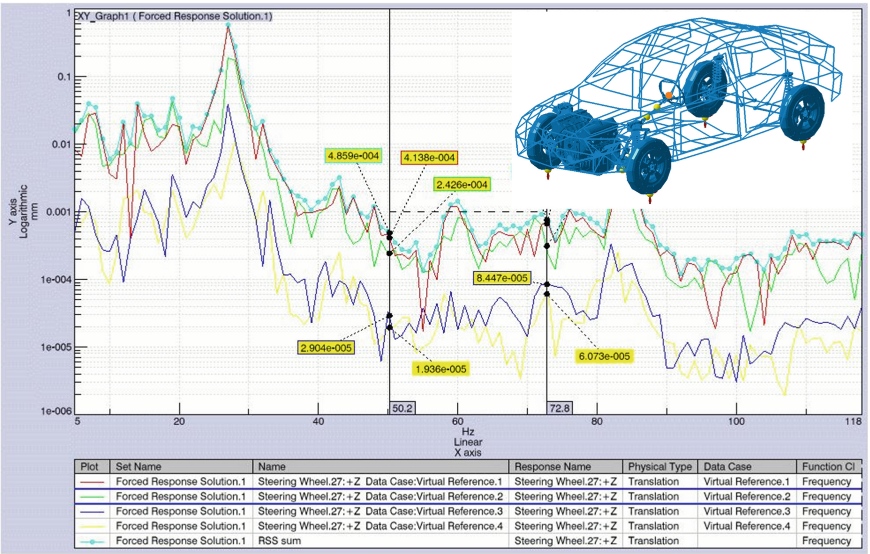

Fig. 5. Total displacement of the steering wheel point generated by the virtual spectra

The total displacement spectrum is shown for all virtual references (principal components) together and the displacements (responses) for each virtual reference separately over the complete frequency range. The responses (vibrations) for all principal components (virtual references) are added by using the RSS averaging option, because the energetic sum must be used as these responses are referenced towards the orthogonal (uncorrelated) references.

4.2 Panel Contribution Analysis Process

Identification of problematic area in early stages of vehicle development is considered as the most efficient way to reduce time and cost of design. Panel contribution analysis is introduced as one of the most effective diagnostic method to identify the source of interior acoustic problem. In this paper identification of panel contribution is realised using measured road loads derived from a road profile measurement.

The vibro-acoustic performance of the car body is investigated by using finite element analysis. The analysis process is shown in Fig. 6.

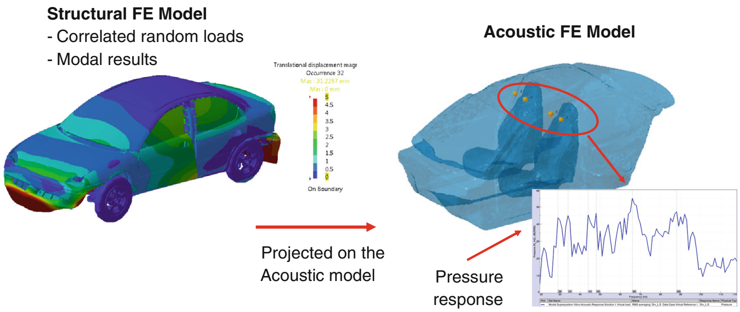

Fig. 6. Vibro-acoustic analysis process

At first structural model of the car is made. Modal analysis of the structure allows identification of the normal modes and frequencies. The structure is excited with virtual loads (principal components) at the points of contact of the tires with road. Inside the cabin is meshed yielding of the acoustic mesh. The cab structural mesh is projected to the interior acoustic mesh. Sound pressures near the driver and passenger ears are analyzed.

Contributions of thirteen dominant panels are calculated for excitation forces. Individual and total pressure responses spectra in the driver ears depending on the virtual references are shown in the Fig. 7.

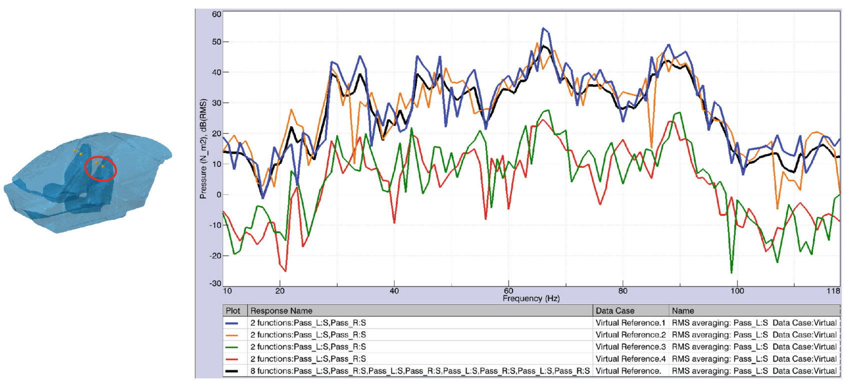

Fig. 7. Individual and total pressure responses spectra in the driver ears

Panel contributions at different frequencies in the driver left ear acoustic pressure are presented in Fig. 8.

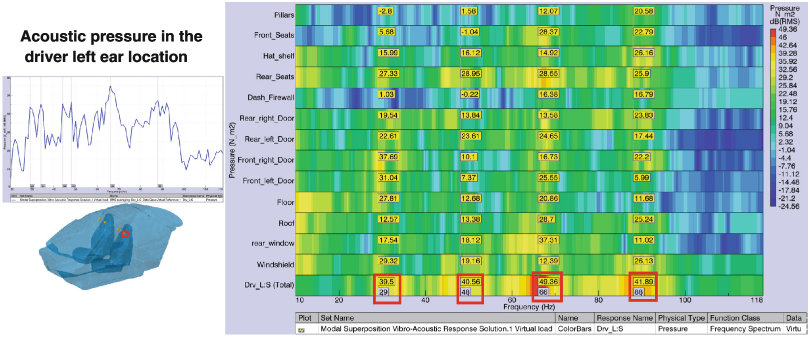

Fig. 8. Panel contributions in the driver left ear acoustic pressure

Major panel contributions in the driver left ear acoustic pressure for specified values of frequency are shown in Fig. 9.

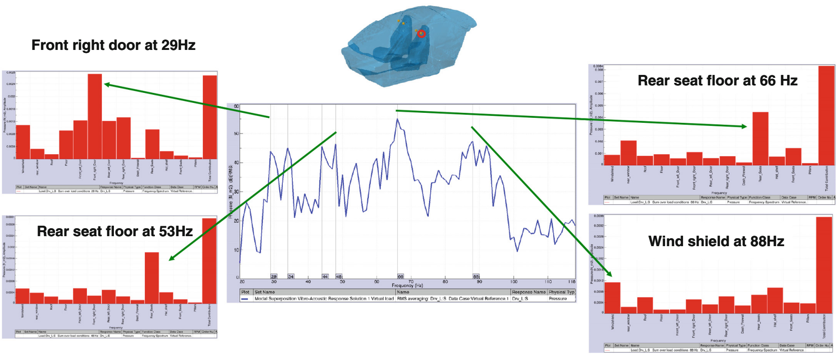

Fig. 9. Major panel contributions in the driver left ear

5 Conclusions

Coherence and Principal Component Analysis methods are commonly applied to analyse the physical interrelations between stationary multichannel test data. Non-coherent vibrations decomposing into a set of coherent vibrations (main components) avoid overloading responses to such input loads. Figure 10 shows the RMS averaging of the acoustic pressure spectra in the analyzed target responses (left, right ears of the

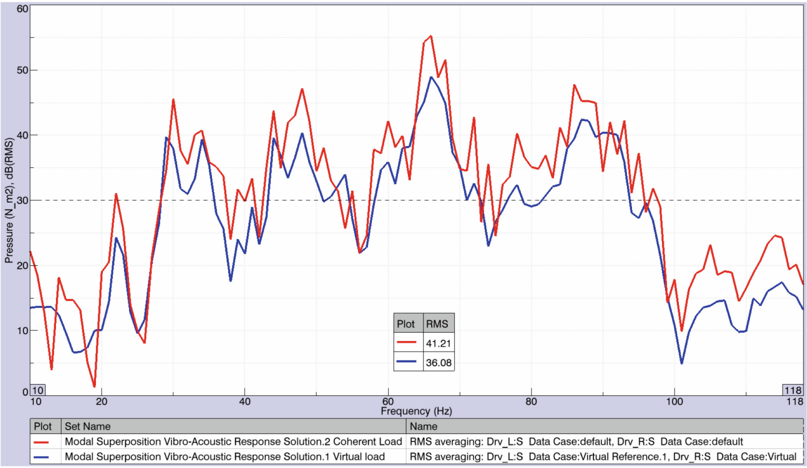

Fig. 10. Acoustic pressure spectra responses in the target locations for correlated vs. coherent input loads

driver and passenger car) using correlated (red color) vs. coherent loads (blue color). The response overloading is estimated as being 5 dB.

Panel contribution analysis ranks a set of panels with respect to their sound pressure level contribution at a target position. The predicted contributions from all panels under study are combined to find their sum.

The major panel contributions in the driver left ear acoustic pressure are the following: front right door at 29 Hz, rear seat floor at 53 Hz, rear seat floor at 66 Hz and windshield at 88 Hz. An example of structural modification proposal for a new model car is presented in Fig. 11.

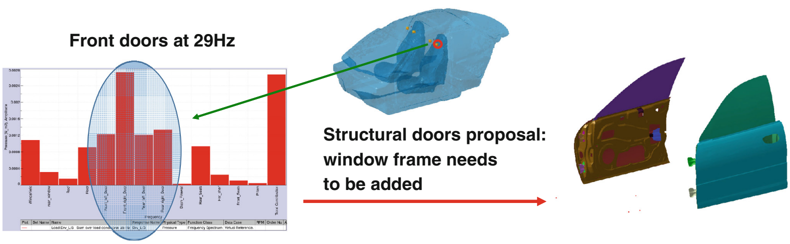

Fig. 11. Structural modification proposal for the front doors

Based on structural analyses one can conclude that for a diminishing of the road noise generated by the front doors at 29 Hz, the windows frame needs to be added.

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