INTERIOR ROAD NOISE ANALYSIS WITH PRINCIPAL COMPONENTS

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ABSTRACT As powertrain noise is better and better controlled, road noise inputs become more important. The interior road noise of a car is mainly induced by the wheels rolling over the road surface. Each of the four wheels act as an independent and uncorrelated excitation input. To rank the energy transfer from each input to the interior, a Transfer Path Analysis (TPA) needs to be made - which requires operational vibration measurements. However due to the multiple uncorrelated inputs, phase relations vary continuously. It is therefore necessary to separate the operational data into sets of "independent phenomena" by means of a Principal Component Analysis (PCA). A TPA can then be carried out for each independent phenomenon. Operational deflection shapes referenced to these principal components share the physical phenomena. The details of the methodology are discussed and a discussion of the results on a car shows that the method gives accurate results for full vehicle testing.

1. INTRODUCTION

Road noise is increasingly becoming more apparent in the overall noise level within a car - often because Transfer Path Analyses (TPA) have successfully been applied to reduce the once predominant powertrain noise.
Road noise deals with multiple independent and mutually uncorrelated excitation inputs due to the rolling of the wheels over the road surface.
The amount of energy transmitted from the wheels to the car's interior is determined by the dynamic properties of the suspension and the body. This energy can be transmitted through several paths. The main transmission paths being the shock absorbers, suspension triangles, subframe and/or twistbeam connection points. To rank these transmission paths in importance a Transfer Path Analysis is carried out. For a TPA, operational vibrations need to be acquired.
A characteristic of wheel excitation is that several mutually incoherent inputs act simultaneously on the suspension. Due to these multiple uncorrelated inputs, the various phase relationships - between accelerations, between acoustic pressures, and between accelerations and acoustic pressures - are varying continuously. The classic single reference technique used to acquire operational vibrations for powertrain noise applications can not deal with multiple uncorrelated inputs. It is therefore necessary to separate the operational data into sets of "independent phenomena" by means of a Principal Component Analysis (PCA).
The operational data set derived for each independent phenomenon can then be used to carry out an independent TPA for each phenomenon, or to visualize its operational deflection shape.
This paper gives an overview of Transfer Path Analysis and Operational deflection shape analysis by the use of Principal Component Analysis to separate the operational data into sets of "independent phenomena".

2. NOTATION

P total interior acoustic pressure
P_i partial pressure contribution related to degree of freedom i
F_i operating force in DOF i
H_i^* vibro-acoustic transfer function P/F_i
$\{\ddot{x}\}$ vector containing an acceleration spectrum for each of the n response degrees of freedom.
$[H^*]$ n x n matrix containing all transfer functions $\frac{\ddot{x}}{F}$ between all force inputs and all acceleration measurement locations.
$\{F\}$ the force inputs
Nr number of reference signals
Ns number of significant eigenvalues number of independent phenomena
M number of averages
$[X(f)]$ acceleration matrix of the reference signals with dimensions (Nr, M)
$[S_{xx}(f)]$ crosspower matrix
$[U(f)]$ Unitary (Nr, Nr) eigenvector matrix of $[S_{xx}(f)]$
$[U(f)]_{N_s}$ matrix of Ns first eigenvectors
$[X'(f)]$ (Nr, M) matrix of principal components
$[X'(f)]_{N_s}$ matrix containing Ns principal components or "independent phenomena".
$[S'_{xx}(f)]$ diagonal matrix, containing the eigenvalues of $[S_{xx}(f)]$ in descending order
S_{ii} autopower of response i
S'_{jj} autopower of principal component j
S'_{ij} crosspower between principal component j and response I
γ_{ij}^2 virtual coherence
$[Y(f)]$ matrix of output signals
$Y_{i,j}$ spectrum of signal i referenced to principal component j

3. PRINCIPAL COMPONENT ANALYSIS

Principal component analysis aims at finding a set of unit linear combinations $[U]$ of the measured responses, resulting in a new set of uncorrelated signal spectra $[X']$: the principal components. (1)

$$[X(f)] = [U(f)][X'(f)]$$

The crosspower matrix of these uncorrelated signals should be diagonal.

$$[S'_{xx}(f)] = [X'(f)][X'(f)]^h \qquad h : \text{hermitian}$$

Diagonalizing the crosspower matrix of the original signals can be performed by computing the eigenvalues and related eigenvectors.

$$[S_{xx}(f)] = [U(f)][S'_{xx}(f)][U(f)]^h$$

$[U(f)]$ is the eigenvector matrix of crosspower matrix $[S_{xx}(f)]$.
$[S'_{xx}(f)]$ is a diagonal matrix, containing the eigenvalues of $[S_{xx}(f)]$ in descending order.
These eigenvalues are real and non-negative because $[S_{xx}(f)]$ is Hermetian.
They can be considered as the autopower spectra of the principal components $[X'_i(f)]$ which are totally uncorrelated (crosspower spectra are zero).
The number of non-zero eigenvalues, Ns, can be considered as the number of "independent phenomena" interacting on the structure. The acceleration signals $[X_i(f)]$ can be written as a linear combination of those "independent phenomena".

$$[X(f)] = [U(f)]_{Ns}[X'(f)]_{Ns}$$

The elements of each eigenvector can then be viewed as transmissibility functions from the principal components $[X'_{\cdot}(f)]$ to the physical locations.

The virtual coherence function is defined as the ordinary coherence between the i-th signal and the j-th principal component.

$$y_{ij}^2 = \frac{|S'_{ij}|^2}{S_{ii} \cdot S'_{ii}}$$

The virtual crosspower spectrum $S_{ij}'(f)$ is the crosspower spectrum between the i-th signal and the j-th principal component.

The virtual coherence function is a helpful tool in finding the importance of the calculated principal components and estimating the number of important phenomena that contributes to the motion or sound pressure in a specific location.

If the sum of the first Ns virtual coherences approximates 1, the dimensionality in that location is estimated Ns.

The sum of all virtual coherences will equal the multiple coherence for each signal.

In practice a principal component analysis is carried out on the crosspower matrix of the references. For each principal component or "independent phenomenon", the virtual crosspowers with all response points form the virtual operational deflection shapes. If the output signals are defined by a matrix $[Y(f)]$:

$$[S_{YX'}(f)] = [Y(f)][X'(f)]_{Ns} = [S_{YX}(f)][U(f)]_{Ns}$$

The virtual crosspowers are obtained by multiplying the ordinary crosspower matrix by the eigenvector matrix.

Out of the virtual crosspower, referenced spectra are calculated.

The number of references equals Ns and for each DOF Ns referenced spectra are obtained :

$$Y_{i,j} = \frac{S'_{ij}}{\sqrt{S'_{jj}}}$$

Index i in the formulas above could be an acceleration or an acoustic pressure. For a certain principal component j all referenced spectra are fully coherent and spectra referenced to different principal components are uncorrelated.

4. PCA APPLICATION ON A CAR SUSPENSION

Operational vibrations need to be measured to carry out a Transfer Path Analysis. For engine noise those operational vibrations are always measured on a roller bench to be able to control the engine speed and the engine load. Other advantages of a roller bench are less disturbance of road excitation and an easy instrumentation.

To investigate road noise, operational vibration measurements can no longer and don't have to be done on a roller bench because of several reasons.

The main reason is the phase relation that exists between the partial pressures generated by the 4 different wheels. Each wheel can be considered as an independent excitation input and excites structural and acoustical resonances. These resonances generate a partial pressure with a certain phase relationship for each excitation input. Figure 1 shows an example of the partial pressures at 46 Hz with the corresponding phase information in a vector diagram.

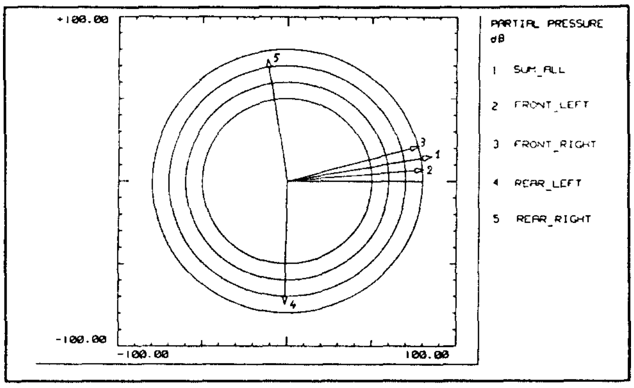


Figure 1 : Vector Diagram of partial pressures

For this car and at this frequency the front wheel generate partial pressures which are almost in phase with each other while the rear wheels generate partial pressures which are almost counterphase with each other. The resulting vector of the rear wheels is relative small and cancels a part of the partial pressures generated by the front wheels. Since the rear wheels cancel the noise of each other and even a part of the total noise, it would be unwise to put a lot of effort in reducing the noise of the rear wheels at this frequency. A road noise analysis on a roller bench will never be able to find these phase relationships because only one or two wheels can than be investigated at the same time.

Other reasons why a roller bench is no longer necessary are :

- the excitation of the wheels is not sufficient with smooth rollers
- control of engine speed and engine load is not necessary because measurements are done at constant speed.

Operational measurements on the road imply that several uncorrelated excitations act on the car. The momentary amplitude and phase relation of the measured DOF's can vary widely, dependant on the time history of the sources.

Therefore a Principal Component Analysis needs to be done to identify the operational vibrations in an unique way.

For a PCA several references are necessary. One can take mechanical vibrations or acoustical pressures as reference. For this analysis 4 acoustical references were used. Figure 2 depicts the autopower of the references.

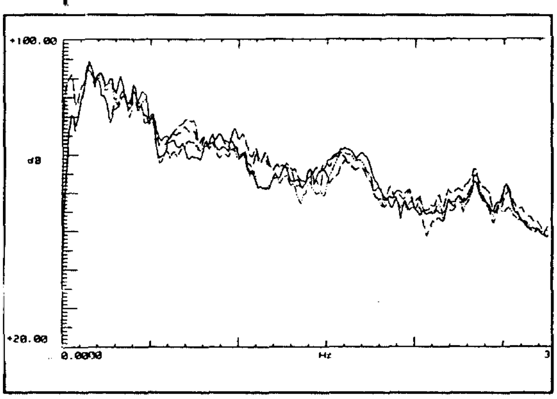


Figure 2 : Interior road noise : autopowers of the 4 reference microphones.

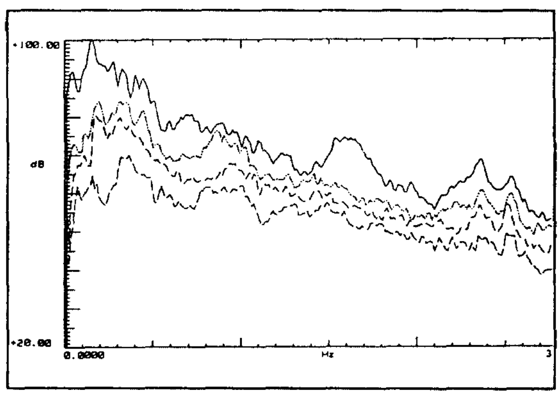


Figure 3 :Principal components

A principal component analysis determines the number of important phenomena present in the system. The principal component are ranked according to its importance (see fig. 3).

Below 80 Hz and within the frequency range (140-180 Hz), only one dominant phenomenon is present, while between 80 Hz and 140 Hz there are 2 important phenomena.

Figure 4 depicts the autopower of a microphone (solid line), the part of the autopower caused by phenomenon 1 (dash-dot-dot line) and the part of the autopower caused by phenomenon 2 (dash line).

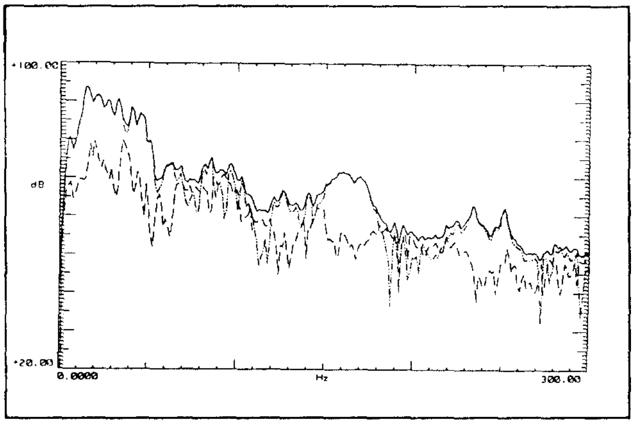


Figure 4 : Autopowers of the microphone : total (-) caused by phenomenon 1 (_..), and caused by phenomenon 2 (- -)

Below 70 Hz and in the frequency range (140 - 180 Hz) the noise is mainly caused by the first phenomenon while between 70 Hz and 140 Hz 2 phenomena contribute to the total noise level. This is in accordance with the importance of the principal components, explained with figure 3.

In order to know what kind of phenomenon causes the noise, on operational deflection shape analysis with the principal components as reference is executed.

Spectra of the measured DOF's are referenced to the principal components as explained in section 3. Figure 5 and 6 give an example of those virtual deflection shapes.

Figure 4 showed that at 26.8 Hz and 159.9 Hz almost all the noise was caused by the first phenomenon.

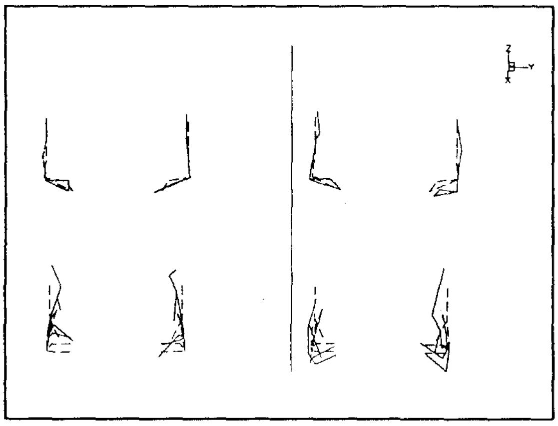


Figure 5 : Operational deflection shape at 26.8 Hz
Left : referenced to the first PRCM
Right : referenced to the second PRCM

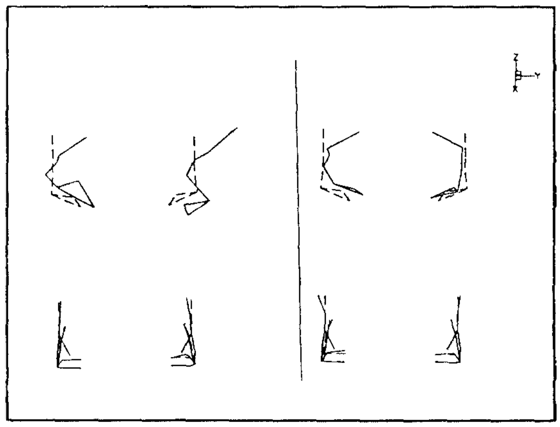


Figure 6 : Operational deflection shape at 159.9 Hz
Left : referenced to the first PRCM
Right : referenced to the second PRCM

One can see in figure 5 that at 26.8 Hz this phenomenon is a up-down movement of the rear wheels while the second phenomenon (not important for the road noise) is an antisymmetrical up-down movement of the rear wheels.

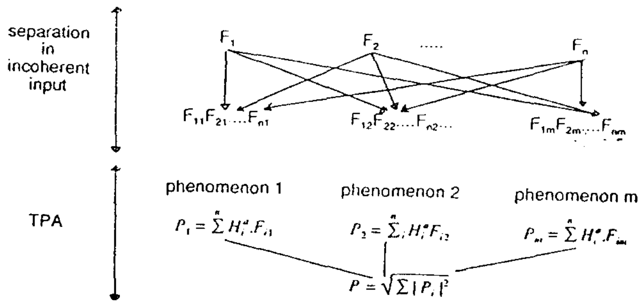
At 159.9 Hz (see fig. 6) the important phenomenon is an antisymmetrical bending of the front shock absorbers and an antisymmetrical up-down movement of the front wheels.

The symmetrical movements (phenomenon 2) are less important for the road noise.

5. ROAD NOISE TRANSFER PATH APPROACH

For Road Noise, the classical (single input) transfer path analysis need to be expanded to a multiple input environment.

Since the operational vibrations determine the operational forces on the mounts of the suspension it is necessary to define the operational vibrations in a unique way.
By using a principal component analysis the operational forces are separated into several sets of coherent signals.



A regular transfer path analysis is carried out on each set.
The final results of each TPA can only be summed in a RMS way, since phase relations exist only between signals coherent with one phenomenon, and not between the incoherent phenomena.

6. CONCLUSIONS

Due to the multiple incoherent inputs involved in road noise, operational vibrations can not be defined in a unique way by using a single reference. Principal component analysis is an efficient technique to define the operational vibrations in a unique way. It separates operational vibrations into sets of coherent signals, each set representing an independent physical phenomenon.
As well operational deflection shapes as a transfer path analysis can be carried out for each phenomenon.

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