Transfer Path Analysis – a Review of 18 Years of Practical Application

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Introduction

18 years ago the Vehicle NVH department in Cologne was a small group of about 12 engineers that owned one power train and two vehicle dynos. In general dyno measurements were performed with 2 channel analogue equipment and XY-plotters, for road measurements mainly 2 channel analogue tape recorders were used.

Figure 1: The FORD Sierra, developed in Cologne in the 80s

Only 5 years later about 90 vehicle NVH engineers worked in the brand new Acoustic Centre Cologne with more than 15 additional facilities. All analogue measurement equipment was replaced with multi-channel digital data acquisition systems and DAT-recorders.

Within these 5 years also several new analysis methods were developed and implemented, one of them was the Transfer Path Analysis (TPA), which replaces the simple detaching tests.

Transfer Path Analysis

The TPA defines an excitation envelope and models each connection to the response side as an operational force F_{oper} that acts on the body with a certain p/F body sensitivity and creates a partial pressure p_i.

$$\vec{p}_{ij} \doteq \left(\frac{p_j}{F_i} \right)_{FRF} \bullet \vec{F}_{oper\_i} \qquad \text{[Pa]} \qquad (1)$$

If all paths are included correctly the vector sum of all partial pressures equals the measured pressure under operation.

$$\vec{p}_{oper\_j} = \sum_i \vec{p}_{ij} \qquad \text{[Pa]} \qquad (2)$$

The first TPA using the stiffness method was done by an external supplier on a FORD dyno. This gave a first insight into the method.

The **stiffness method** calculates the excitation forces F_{oper_i} by measuring the relative displacement across an elastic mount and multiplying this with the dynamic stiffness of the mount.

In the next year the first TPA performed by FORD engineers was done. A high effort was needed to measure the static deflection of the engine mounts (CAE models were rare those days) under different load conditions and to finally measure the dynamic stiffness of the engine mounts in all 3 directions with these static pre-loads.

Based on this experience a strategic decision was made to go for the so called matrix method. This would make the measurement of dynamic stiffness obsolete thus avoiding the time consuming effort to evaluate the static deflections, remove the engine mounts and measure their dynamic stiffness.

The **matrix method** not only needs the body sensitivities p/F and a/F but a complete a/F matrix in order to be able to remove the cross-talk between paths. The resulting accelerations under operation can be expressed as:

$$\begin{bmatrix} a_1 \\ \dots \\ a_i \end{bmatrix}_{oper} = \begin{bmatrix} F_1 \\ \dots \\ F_i \end{bmatrix}_{oper} \times \begin{bmatrix} \frac{a_1}{F_1} & \dots & \frac{a_i}{F_1} \\ \dots & \dots & \dots \\ \frac{a_1}{F_i} & \dots & \frac{a_i}{F_i} \end{bmatrix}_{FRF} \qquad \text{[m/s}^2\text{]} \qquad (3)$$

(inertance matrix)

By inverting the inertance matrix the excitation forces can be calculated out of the measured acceleration under operation.

Although the matrix method was performed before by others [1], in 1991 it still was an exotic approach and no commercial analysis software solution was available. One prerequisite for the matrix method to be efficiently used was the availability of a multi-channel digital data acquisition systems, which just entered the vehicle NVH arena.

The first TPA was done on a front wheel driven vehicle – and gave strange results. Besides the engine mounts and exhaust hangers the front struts and A-arms were included in the TPA model. In order to improve the quality of the results several mathematical strategies were tried out, one of them the Singular Value Decomposition (SVD) approach. The idea was that the results were deteriorated by small eigenvalues of the matrix that translate into high F/a values after the matrix inversion.

In fact the predicted sum of partial pressures improved significantly, but depending on the threshold for the eigenvalues [2], [3].

Evolution of TPA

After a few TPAs it was found out, that the threshold level of the SVD approach needed to be optimized for each TPA individually. Although the overall prediction could be improved by this, the resulting partial pressures sometimes were deteriorated.

⇒ A good agreement between predicted and measured response is a **necessary** condition but **not sufficient** to prove that the TPA model is correct for each path!

By comparing the forces evaluated using the diagonal matrix, band matrix and full matrix with different paths excluded it was found, that adjacent paths with identical movement (e.g. A-arm in X-direction) caused trouble for the matrix inversion. Combining points with rigid body movement to one path solved the matrix inversion problem even without using SVD and gave better insight into the physics of the problem.

The FORD proprietary TPA software was extended to also cover road NVH problems and over determined systems. For road noise problems there was no longer a single coherent source but four partly incoherent excitations. In order to treat this problem in the "normal" TPA way the incoherent excitation must be decomposed into several independent sets of coherent excitations that represent the original excitation as good as possible. This can be done by calculating the principal components but requires a set of reference transducers. The "art" of road TPA is to define a minimum number of reference transducers.

Together with colleagues from FORD US a joint project was performed in Dearborn in 1995 that should answer open questions around road TPA topics:

- matrix method versus stiffness method
- de-coupled versus coupled strategy
- find out best strategy for reference locations (body, knuckle, mics)

The lessons learned were verified with several road TPAs and finally made public [4].

In the beginning TPA was misunderstood to be the solution for complex NVH problems. But TPA in general does not solve the problem, it is just a very structured approach that efficiently guides further investigations like:

- detailed operational deflection shape analysis
- panel radiation analysis (vibration on panels regarded as virtual input forces)
- detailed Acoustic Source Quantification (ASQ)

Limitations of TPA

Even after the experience of more than 50 TPAs the interior noise prediction was not perfect due to inherent difficulties:

- FRFs are measured in "cold" condition without a driver, operational data in "hot" condition with driver (mass and volume effect); this can be partly overcome with reciprocal NTFs in hot condition, but then the driver is moving around
- Engine torque pre-load only during operation, not during FRF measurements
- TPA model has 3 DOFs per path, real world has 6 DOFs (3 rotational DOFs)

In general the prediction is better for part throttle operation (less torque) and e.g. at co-drivers seat (lower influence of driver). Due to above limitations perfect agreement between measured and predicted response cannot be achieved.

Optimum frequency range for TPA

A good agreement between measured and predicted response can only be achieved in a limited frequency range. At low frequencies the cross-talk between paths increases due to the stiff body structure. This makes TPA sensible for small measurement errors (sensitivity, orientation etc.). At high frequencies the body structure becomes more local. This is a problem e.g. for engine mounts mounted with several screws to the body. In general a good agreement can be achieved between 40 and 500 Hz, in special cases up to 750 Hz.

TPA within the development process

In the last 15 years development cycles became significant shorter. This was achieved by intensive use of CAD/CAE tools and a more structured development process. The total vehicle was down cascaded into systems, subsystems and components with targets on each level. This allows to design components and subsystems independently and ensures that the complete system and vehicle will fulfil the targets.

TPA was used for benchmarking and thus supports the target setting process. However, the systems approach needs a hybrid tool that could combine targets with measurement and CAE data and predict the interaction of the subsystems. The FORD proprietary tool is called INCA (Interior Noise Contribution Analysis).

In order to be competitive all automotive companies are trying to further reduce the cycle time and the development costs by more intensive usage of CAD/CAE tools and reduction of the number of prototype phases and vehicles. This will reduce the available time for tests, so tests must be performed in a shorter time frame and results must be available sooner to support the shorter development phase.

For a complex tool like TPA this requires to reduce the number of paths, because the instrumentation is a big part in the total test time. However, this is very critical for the matrix inversion method. After many years and > 100 TPAs with comparison of diagonal, band and full matrix it was seen that the ranking of paths in general is very similar with all 3 methods.

So for **time critical tasks** less paths are included. Although the complete transfer matrix is measured for the evaluation mainly the diagonal matrix is used. For road TPAs no reference transducers are defined and only autopower spectra are measured. Even if the predicted response is overestimated:

- the point inertances [(m/s²)/N] show structural problems
- the NTFs [Pa/N] show structural and cavity problem
- the operational acceleration together with point inertance shows excitation problem
- operational deflection shapes (accelerations or pressures) help to understand the physics
- the comparison of complex and energetic sum of paths (power train TPA) is used as an indicator for the robustness of the design.

New trends in TPA

Diesel power trains have become more and more popular in the last 10 years. With more stringent CO_2 targets and higher oil prices there is a run for lower fuel consumption. This is achieved by a harsher combustion which is also valid for petrol power trains with direct injection.

This deteriorates the sound quality and cannot be handled efficiently with classical TPA methods but need **time domain strategies**. Covering the frequency range up to 8 kHz is a major challenge for these methods (see "Optimum frequency range for TPA").

In order to overcome some limitations of the TPA (difference between FRF and operational measurement) and to speed up the measurement process the Operational TPA allows to omit the FRF measurement but uses the different sets of operational responses at different rpms to estimate the FRFs. This involves mathematical strategies like singular value decomposition, principal component analysis and least square approximation to solve the transfer matrix problem and to distinguish between road and power train input.

As all paths need to be measured in parallel this method can also provide a prediction of the time signal. Again the frequency range up to 8 kHz is a major challenge.

Currently there is only limited practical in-house experience available. The future will show whether these time domain methods will provide stable and reliable results. They will be more used for sound quality fine tuning towards the end of the development process.

References

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