Innovative Approaches to Fast Transfer Path Analysis

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Abstract

While Transfer Path Analysis (TPA) is an accepted tool for NVH troubleshooting, a bottleneck towards even more widespread use is the test time to build the full data model. Extensive Frequency Response Function testing is required next to the in-operation tests. Recent procedures such as Fast, Multilevel and Operational TPA, address this, however often introducing new constraints related to accuracy and interpretability. Hence a new approach is proposed, using a parametric model for the load estimation. This makes the method scalable, enabling the engineer to use simpler or more complex models depending on the required accuracy. The method is applied to industrial problems and compared with existing approaches, showing the real-life advantages.

Introduction

Transfer Path Analysis (TPA) is an experimental technique to identify the vibro-acoustic transfer paths in a system, from active components, generating structural and acoustic loads, through physical connections and along airborne pathways, to target locations at the passive system side.

The formulation is based on a source-system-receiver model, expressing the total response as a sum of partial responses (contributions) resulting from individual loads acting at a localized interface. Each partial response is described by the load at the interface, and a system response to this load [1]. This corresponds to cutting the system at the interface into an active part generating loads and a passive part reacting to the loads. For structural loads, this typically corresponds to physical connections. For acoustic loads, a discretization by omnidirectional point sources is typically applied [2].

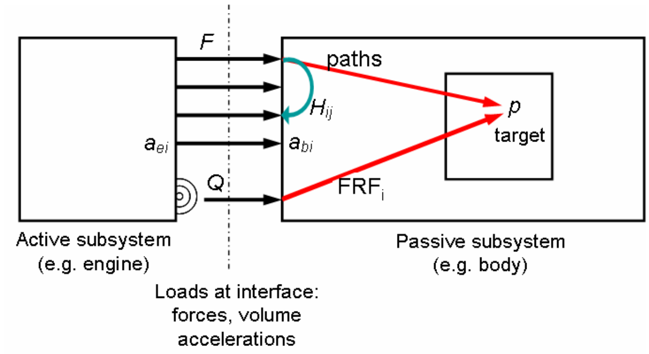


Figure 1: TPA model.

This can be expressed as follows:

$$y_k(\omega) = \sum_{i=1}^{n} FRF_{ik}(\omega) * F_i(\omega) + \sum_{j=1}^{p} FRF_{jk}(\omega) * Q_j(\omega) \qquad (1)$$

with $F_i(\omega)$ ($i = 1,\dots,n$) the structural loads, $Q_j(\omega)$ ($j = 1,\dots,p$) the acoustic loads, and $FRF_{ik}(\omega)$ and $FRF_{jk}(\omega)$ the system response functions from loads to targets. Visualizations of the contribution results allow to quickly assess critical paths and frequency regions. The separation into loads and FRF's is the key to identify dominant causes and propose solutions.

The test procedure to build a conventional TPA model typically requires two basic steps: (i) identification of the operational loads during operation (e.g. run-up, on the road or on a chassis dyno); and (ii) estimation of the FRF's from excitation tests. The procedure is similar for both structural and acoustical loading cases, but the implementation is governed by the nature of the signals and loads.

The measurement of the FRF's between input loads and target response(s) is the easiest to control well. Advanced instrumentation and procedures based on the reciprocity principle have been developed and are commonly used.

The identification of the operational loads is the main accuracy constraining factor. For structural excitation, there exist three ways to identify the forces, by measurement (often not feasible), through a mount stiffness approach and indirectly, through matrix inversion of a local receptance matrix [3]. The latter method is the most general but requires a large set of FRF measurements to be performed, which is a bottleneck towards generalized industrial use.

ALTERNATIVE METHODS

Several methods have been proposed to speed up the TPA process: Fast TPA, Multilevel TPA and Operational TPA.

FAST TPA

In many NVH applications, a first and key question is to identify which subsystems are the main contributors to the noise rather than identifying in detail each of the paths. A fast testing procedure, "Fast TPA" [4], was hereto developed extending the traditional in-operation measurements at subsystem and target locations by a limited number of FRF tests, defined for the same response locations and for a limited set of arbitrary excitation points on the concerned subsystems. Combining this FRF matrix with the operational responses allows the identification of a set of "virtual" operational add-on loads which can be used in a forward contribution analysis estimating the subsystem contribution to the target.

"Fast TPA" is considered to be a valid alternative for applications where a fast assessment of the critical sources or subsystems is needed. It reuses existing instrumentation, involves limited extra testing, does not require removal of the active systems and is compatible with the way of working of NVH analysts performing ODS and TPA studies. While it does not allow the determination of the actual loads at the interfaces, the virtual add-on loads can be transferred to a CAE model and used for response calculations.

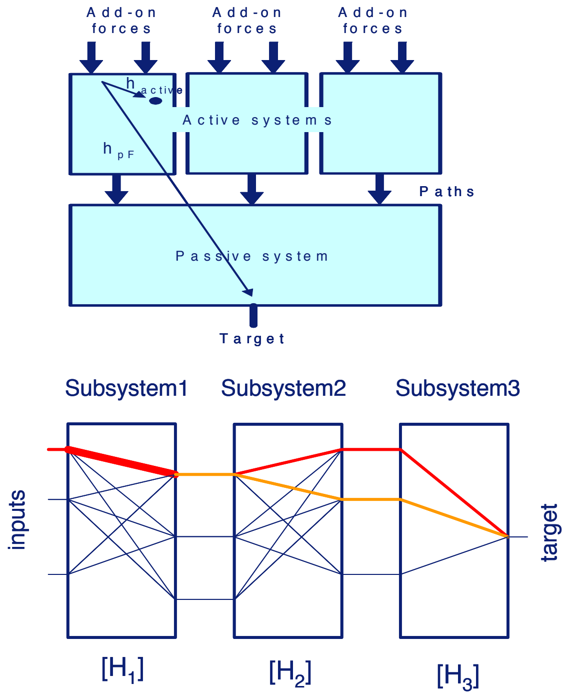


Figure 2: Fast TPA (top), Multilevel TPA (bottom).

The Fast TPA concepts can be extended to study a “chain” of linked subsystems in the noise path (Figure 2 bottom). This method is referred to as Multilevel TPA [4].

OPERATIONAL TPA

The recently developed Operational Path Analysis (OPA) approach [5, 6] requires only operational data measured at the path inputs (passive-side mount accelerations, pressures near vibrating surfaces, nozzles and apertures) and target point(s). The goal is to derive “TPA-like” results from operating tests only. This is achieved by using a formulation expressing the target response using responses measured at the load locations instead of the loads themselves:

$$p(\omega)=\sum_i T_i(\omega)a_i(\omega)+\sum_j T_j(\omega)p_j(\omega) \qquad (2)$$

The method is essentially a transmissibility method [7], characterizing rather the co-existence between the target response(s) and path references, without assessment of the causal relationship. The transmissibilities are estimated from the operational data, for example using the H_1 estimator:

$$p=\sum_i T_i.a_{bi} \Rightarrow \{p\}=\{T\}\{a_b\} \Rightarrow \left\langle p.a_b^{'}\right\rangle.=\{T\}\left\langle a_b.a_b^{'}\right\rangle \qquad (3)$$

$$\{T\}=\left\langle p.a_b^{'}\right\rangle\left\langle a_b.a_b^{'}\right\rangle^{-1} \qquad (4)$$

The basic condition for performing this operation is the invertibility of the autopower matrix, which requires special attention during the test definition to ensure decorrelation. In the lower frequency ranges, the input vibrations may be largely coherent because of the strong modal behaviour, making the autopower matrix rank deficient. In such cases a pseudo-inverse solution using principal component analysis or singular value decomposition can be applied.

The OPA method is indeed quite time-efficient, but results must be considered with care [6]. One key limitation is the potential cross-coupling between the path references. Since each body acceleration may depend on forces at all mounts, the split of target responses in reference accelerations is not necessarily correct, e.g. due to modal behaviour. Co-existence of signals does not imply causality. Due to the apparently simple presentation of the results, this cross-coupling effect hence may lead to a false interpretation of significant paths and wrong engineering decisions.

Other potential errors are due to missing paths in the analysis. Contributions of such missing paths are distributed over the other ones, introducing hard to recognize errors. Due to the backward-forward use of the same data, a good synthesis of summed contributions is not representative for the completeness and quality of the results.

So while offering a nice potential for fast troubleshooting, due to postprocessing multi-reference operational deflection shape data, care must be taken in interpreting the OPA results in terms of actual path contributions.

NOVEL TPA METHOD USING PARAMETRIC LOAD MODELS

This paper introduces a novel TPA approach, which combines the efficiency of the operational path method and the effectiveness of the existing conventional TPA methods. The novelty is in the identification of parametric models for the operational load, characterizing the operational forces and acoustic loads as a function of measured path inputs such as mount accelerations and acoustic pressures. The parametric load models are estimated from in-situ measured operational path inputs and target response signal(s) and from transfer path FRF’s using mathematical techniques, such as the Least Squares (LS) estimation approach. Extra acceleration or pressure indicators can be included to obtain more robust parameter estimations but this is optional.

Figure 3 shows a schematic representation of the different variables to be measured and identified.

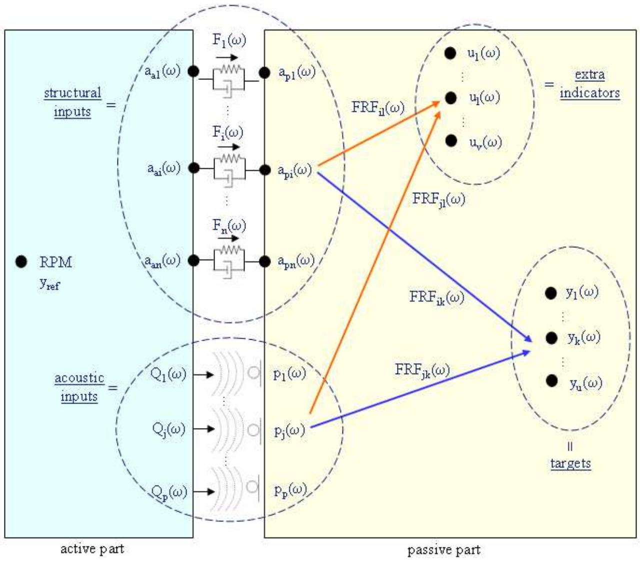


Figure 3: Schematic representation of a system with an active and passive system part.

It presents a system with an active part generating forces $F_i(\omega)$ ($i = 1,\ldots, n$) and acoustic loads $Q_j(\omega)$ ($j = 1,\ldots, p$) and a passive part reacting to these loads. An example of such a system is a vehicle body on which a powertrain is mounted. The powertrain forms the active part of the system, while the body with passenger compartment is the passive part.

The method requires collecting following data:

- Operational responses during run-up/down (target pressures and/or accelerations and extra indicators)
- Operational path inputs during run-up/down (structural active and/or passive-side accelerations and acoustic path inputs)
- FRF's from forced excitation tests (loads to targets and loads to additional indicators if used

The new TPA method comprises 5 major steps.

Phase 1: operational measurements. These can be single or multiple run-up or run-down. All mount accelerations and pressure inputs and all responses at the target(s) and indicators are measured synchronously. Cross spectra or order functions are estimated for all inputs and responses.

Phase 2: FRF measurements (direct or reciprocal) between the input loads and target response(s).

Phase 3: estimation of parameteric load models, modelling the operational forces and acoustic loads as a function of the acceleration and pressure path inputs:

$$F_i(\omega) = f(parameters, a_{ai}(\omega), a_{pi}(\omega))$$

$$Q_j(\omega) = g(parameters, p_j(\omega)) \qquad (5)$$

Substituting the load models in the TPA formulation (1), yields equation (6). This also holds for all extra indicators.

$$y_k(\omega) = \sum_{i=1}^{n} FRF_{ik}(\omega) * F_i(parameters, a_{ai}(\omega), a_{pi}(\omega))$$

$$+ \sum_{j=1}^{p} FRF_{jk}(\omega) * Q_j(parameters, p_j(\omega)) \qquad (6)$$

The parametric models may be any suitable model characterizing the loads. In case of soft mounts, for example, an SDOF or a multi-band model with bandwise constant complex mount stiffness may be used. For rigid connections and acoustic loads, a multi-band model can also be used to describe the relation between loads and path inputs, but the frequency bands are typically smaller than for soft mounts.

For a given number of operational path inputs, response data and FRF's, the above equations lead to a linear system of equations that can be solved for the model parameters (e.g. m_i, c_i and k_i in case of SDOF), for example by a Least Squares (LS) estimation approach. The more information is used, i.e. the more orders, targets and indicators, the more accurate the model parameter estimations can be. The use of balancing factors between structural and acoustic terms helps improving the parameter estimations.

Phase 4: identification of operational loads by substituting the estimated model parameter values.

Phase 5: computation of path contributions for each target point, by multiplying loads with the corresponding FRF. Visualizations of the path contribution results enable the assessment of critical paths and frequency regions.

AUTOMOTIVE EXAMPLE

A TPA analysis was carried out on a 6-cylinder car to assess the novel TPA method and compare it with the classical mount stiffness and inverse force identification methods. The main focus was on the structural noise transfer from the powertrain through 5 mount connections to the acoustic target at the driver's ear. Airborne contributions were not analyzed in this study. The following data were measured:

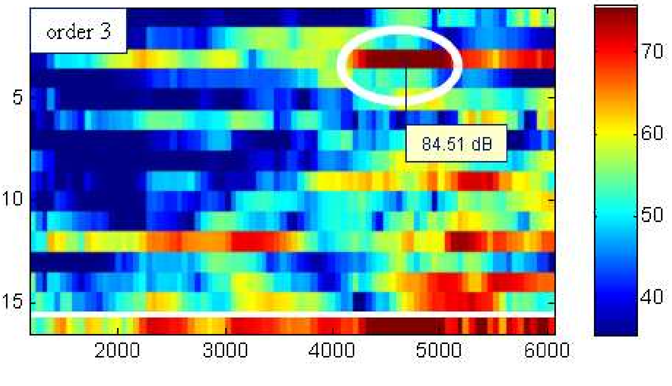
- Operational data during engine run-up from 1200 to 6000 RPM (1 pressure target, 13 extra acceleration indicators at the passive system side, 15 active side accelerations and 15 passive side accelerations
- FRF's from excitation tests (from 15 loads to 1 target and from 15 loads to 15 passive side mount locations and to 13 extra acceleration indicators)

Orders (amplitude and phase as a function of RPM) were tracked for all measured input and response channels. Mount stiffness data (x-,y-,z-direction) were available for all mounts. Both an SDOF and multi-band model were used to characterize the mounts in the new TPA method.

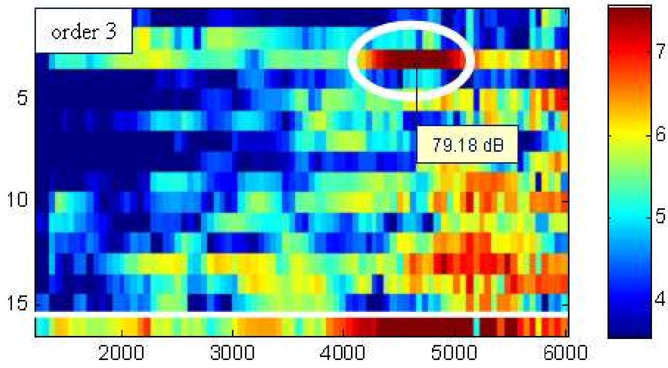
A TPA analysis was done for order 3. This order causes a booming noise in the passenger compartment at 4850 RPM. The following four methods were used:

- Classical mount stiffness method, using mount stiffness data to identify forces
- Classical inverse force identification method using frequency-by-frequency matrix inversion. 420 FRF's from 15 loads to 15 passive side mount accelerations and 13 extra acceleration indicators were used.
- New TPA method using SDOF mount model, using 45 FRF's from 15 loads to 3 acceleration indicators.
- New TPA method using multi-band mount model, assuming constant complex mount stiffness over small frequency bands of 30 Hz and using 195FRF's from 15 loads to 13 indicators.

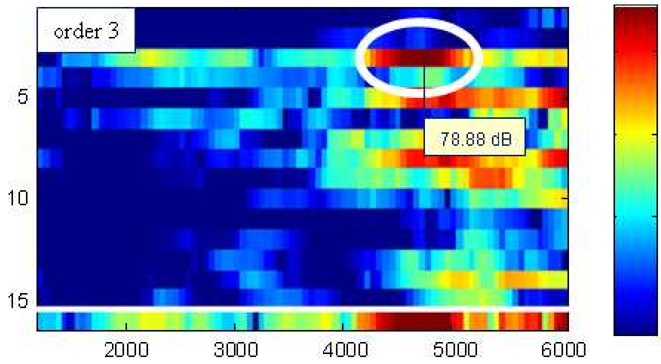
Figure 4 shows the path contribution results for order 3.


(1) TPA mount stiffness method

(2) TPA inverse force identification method



(3) new TPA method using SDOF mount model



(4) new TPA method using multi-band mount model

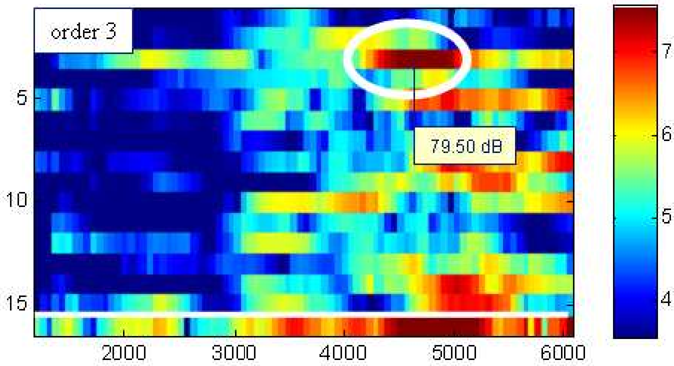


Figure 4: Order 3 path contribution results of the (1) mount stiffness method, (2) inverse force identification method, (3) novel TPA method using an SDOF mount model and (4) novel TPA method using a multi-band mount model.

All four TPA methods are very well capable to spot the critical path (mount 1-z) and frequency region (4850 RPM). The mount stiffness method overestimates the contribution of the critical path at 4850 RPM (+/- 5 dB). This is likely to be due to inaccurate mount stiffness data.

The advantage of the new TPA method is that it is able to correctly spot the critical path without requiring mount stiffness data (not often available and reliable) and measure the complete FRF matrix (huge FRF measurement efforts). For the analyses in Figures 4.3 and 4.4, respectively 3 and 13 acceleration indicators were used to estimate the SDOF and multi-band model, but fewer indicators would have been sufficient. By doing the same analysis with different number of indicators, it turned out that, for this particular example with 15 paths, at least 1 indicator for the SDOF method and 3 indicators for the multi-band model are needed to have a proper conditioning and reliable path contribution results.

CONCLUSION

A new TPA method was developed, combining the speed of the operational path method (OPA) and the effectiveness of the conventional TPA methods. Key is the use of parametric load models characterizing the operational forces and acoustic loads in function of measured path inputs such as mount accelerations and pressures. The proposed TPA method proves to be fast and reliable. It allows balancing between speed of execution and path accuracy. The measurement efforts are small in comparison to the existing inverse load identification technique. Next to the operational measurements of path inputs and target(s), the new TPA method in many cases only requires one reciprocal FRF measurement per target point. Adding extra indicators for improving robustness requires additional FRF measurements.

ACKNOWLEDGEMENTS

The research in this paper is conducted in the context of the Marie Curie Research Training Network “Smart Structures CAE” (MRTN-CT-2006-035559). The financial support of the European Commission is gratefully acknowledged.

REFERENCES

[1] D. De Vis, W. Hendricx and P. van der Linden. Development and integration of an advanced unified approach to structure borne noise analysis, 2nd Int. Conference on Vehicle Comfort, ATA, 1992.

[2] J. Verheij. Experimental procedures for quantifying sound paths to the interior of road vehicles, Proc. 2nd Int. Conference on Vehicle Comfort, Bologna, Italy, Oct.14-16, 1992, p. 483-491.

[3] P. van der Linden and H. Floetke. Comparing inverse force identification and mount stiffness force identification methods for noise contribution analysis, Proc. ISMA, Sept. 2004, Leuven, Belgium.

[4] H. Van der Auweraer, P. Mas, S. Dom, A. Vecchio, K. Janssens, P. Van de Ponseele. Transfer Path Analysis in the critical path of vehicle refinement: the role of fast, hybrid and operational path analysis, Proc. SAE NVH Conf., May 14-17, 2007, paper 2007-01-2352.

[5] K. Noumura and J. Yoshida. Method of transfer path analysis for vehicle interior sound with no excitation experiment, Proc. FISITA 2006, F2006D183, Yokohama, Japan, October 2006.

[6] K. Janssens, P. Gajdatsy, H. Van der Auweraer. Operational path analysis: a critical review. ISMA Conf., Leuven, Belgium, Sept. 2008.

[7] N.M.M. Maia, J.M.M. Silva, A.M.R. Ribeiro, The Transmissibility Concept in Multi-degree-of-freedom Systems, Mechanical Systems & Signal Processing, 15(1), 129-137. Jan. 2001.