Introduction to Transfer Path Analysis
## Transfer path analysis for mechanical industry
The basics, from theory to practice

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Transfer path analysis for mechanical industry
The basics, from theory to practice

• What is TPA?
• Practical considerations
• Strain TPA
• Time TPA
• Component TPA
Transfer path analysis quantifies and visualizes the strengths of selected sources and their contribution via multiple transmission paths to a selected receiver signal.
Transfer Path Analysis
Source-transfer-receiver approach

Most time spent during a TPA is on measuring:
- $F_i$ and $Q_j$ during operation
- FRF functions correctly

$$y_k = \sum_{i=1}^{n} \text{FRF}_{i_k} * F_i + \sum_{j=1}^{p} \text{FRF}_{j_k} * Q_j$$

- Structural
- Airborne
Transfer Path Analysis
Step 1: Which path is contributing?

\[ y_k = \sum_{i=1}^{n} y_i \]
Transfer Path Analysis
Step 2: Why is path contributing?

\[ y_i = H_{ik} F_i \]

- **Source**
  - Structural / Acoustic Loads

- **Transmitter**
  - System characteristics

- **Receiver**
  - Noise & Vibration

Critical loads
Critical dynamics
Worst case scenario
System Engineering for NVH
Source-transfer-receiver model

- Generic structured way to analyze NVH characteristics
- Founded in Test, used in both Simulation and Test

\[ y_k = \sum_{i=1}^{n} \text{FRF}_{ik} \cdot F_i + \sum_{j=1}^{p} \text{FRF}_{jk} \cdot Q_j \]

\[ \text{structural} \quad \text{airborne} \]
Benefits of hybrid modeling:

- Spend less time correlating components. Use test representation of components in a system assembly.
- Promotes component reuse – FE model of new component and reuse of test data from legacy/previous programs.
- Smaller models → Rapid design iteration (e.g. when tuning mounts).
- NVH targets can be cascaded to suppliers.
Hybrid Modeling – Use Case 2 (AUTO OEM)

• Test Tire Component

• Equivalent model of a damper

• FE models of Subframe, Suspension Arms, Knuckle, Strut and Brake


Focus → Modeling accuracy
Hybrid Full Vehicle Road Noise Evaluation (Simcenter and NX Nastran)

- **tyre/wheel**
  - Measured FRFs in LMS Test.Lab

- **Suspension**
  - FEM

- **Trimmed body**
  - Measured FRFs in LMS Test.Lab

- **Loads, e.g. from Test.Lab**

- **Assembly in Simcenter**

- **Full Vehicle in Simcenter**

- **NX.Nastran run**
NVH Results – Post-processing in Simcenter Noise and Vibration Modeling

Insight
- Identify the problem

Contributions
- Modal Contribution Analysis
- Panel Contributions Analysis
- Grid Contributions Analysis
- Path Contributions Analysis
- Energy Contribution Analysis

Understanding Response
- Operational Deflection Shapes
- Equivalent Radiated Power

Problem
- Which Frequency?

Which Modes?
Which Paths?
Which Grids?
Which Panels?
Which ODS?
Transfer Path Analysis
What needs to be measured?

During operations:
• Forces going into the structure, requires in general quiet some measurements
• Acoustical sources
• Target locations

In the lab: measurement of the FRF, is also a tedious job

In general, TPA is a measurement intensive application
OPA method

Only operational measurements required:
• Accelerations at the force locations
• Pressures at the Acoustical sources
• Target locations

Fast method, takes ±1 day of measurements

Transmissibility method

\[ y_k = \sum_{i=1}^{n} T_{ik} \ast a_i + \sum_{j=1}^{p} T_{jk} \ast p_j \]

- structural
- airborne
OPA method:
Potential problems for wrong results: cross-coupling

\[ y = T_1 a_1 + T_2 a_2 + T_3 p_3 \]

Where each acceleration/pressure can be written as:

\[ a_i = H_{1i} f_1 + H_{2i} f_2 + H_{3i} Q_3 \]
OPA method:
Potential problems for wrong results: cross-coupling

E.g.

\[ a_2 = H_{12} \cdot f_1 + H_{22} \cdot f_2 + H_{32} \cdot Q_3 \]

Normally

\[ H_{22} f_2 \gg H_{12} f_1 + H_{32} Q_3 \]

Or the acceleration for a path is normally proportional to the force at that location

\[ a_2 \approx f_2 \]
OPA method:
Potential problems for wrong results: cross-coupling

With cross coupling it can happen that e.g. $H_{12}f_1 >> H_{22}f_2 + H_{32}Q_3$

Or the acceleration at one location is caused by a force at another location, causing this path, e.g. 2, to be considered to be the largest contribution while the cause is due to a force at another location

$T_2a_2 > T_1a_1 and T_2a_2 > T_3p_3 due force at f_1$
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2. Practical considerations
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Transfer Path Analysis
Operational measurements

During operations:
• Forces going into the structure, requires in general quiet some measurements
• Acoustical sources
• Target locations

In the lab: measurement of the FRF, is also a tedious job

In general, TPA is a measurement intensive application
Test Based TPA
Process Overview

Step 1: Preparation
Step 2: Operational Measurements
Step 3: FRF Measurements
Step 4: TPA
Transfer Path Analysis:
Requirements: One integrated process

Step 1: Preparation
Step 2: Operational Measurements
Step 3: FRF Measurements

Signature Testing

Impact Testing
MIMO FRF Testing
MIMO Sine Testing

Excitation Hardware: Simcenter QSources
Transfer Path Analysis: Simcenter QSources
Requirements: Efficient & Accurate FRF Acquisition

Reciprocal FRF excitation hardware
- Fast installation
- High noise levels (>100dB)
- Internal sound source strength measurement
- Omni-directional sources

Direct FRF excitation hardware
- Miniaturized to the maximum
- Efficient installation, auto-alignment and no external support necessary
- Integrated force and local acceleration sensors
- Enables excitation at body engine/suspension interfaces
- Wide frequency range
Transfer Path Analysis: Requirements: All Load Estimation Methods

Step 4: TPA

Load Estimation Methods
- Direct Measured
  - Mount Stiffness
  - Single Path Inversion
    - Single Source – Multiple Indicator
  - Matrix Inversion
    - Multiple Source – Multiple Indicator
- Simcenter OPAX
  - Multiple Source –

Structural

Airborne
Transfer Path Analysis
Load identification: mount stiffness method

\[ F_i(\omega) = K_i(\omega) * \left( \frac{a_{ai}(\omega) - a_{pi}(\omega)}{-\omega^2} \right) \]

- Operational accelerations at both sides of mount
- Operational forces
- Mount stiffness

 mounts...

Source

active side

K_i

F_i

passive side

Body

...
Transfer Path Analysis
Load identification: matrix inversion method

FRF matrix

\[
\begin{bmatrix}
F_1(\omega) \\
F_2(\omega) \\
M \\
F_n(\omega)
\end{bmatrix} = \begin{bmatrix}
H_{11}(\omega) & H_{21}(\omega) & \Lambda & H_{n1}(\omega) \\
H_{12}(\omega) & H_{22}(\omega) & \Lambda & H_{n2}(\omega) \\
M & M & M & M \\
H_{1v}(\omega) & H_{2v}(\omega) & \Lambda & H_{nv}(\omega)
\end{bmatrix}^{-1}
\begin{bmatrix}
a_1(\omega) \\
a_2(\omega) \\
a_v(\omega)
\end{bmatrix}
\]

operational forces

indicator accelerations
Direct Measured  
*Direct measured forces*

---

**Mount Stiffness**

\[ F(\omega) = K(\omega)[X_s(\omega) - X_t(\omega)] \]

---

**Single Path Inversion**
- Single Source – Multiple Indicator

\[ F_{1}^{\text{oper}} = \begin{bmatrix} F_1^{\text{oper}} \\ F_{1001}^{\text{oper}} \\ F_{1002}^{\text{oper}} \\ F_{1} \end{bmatrix}^{-1} \begin{bmatrix} \omega_{1}^{\text{oper}} \\ \omega_{1001}^{\text{oper}} \\ \omega_{1002}^{\text{oper}} \end{bmatrix} \]

---

**Matrix Inversion**
- Multiple Source – Multiple Indicator

\[ \begin{bmatrix} F_{1}^{\text{oper}} \\ \vdots \\ F_{n}^{\text{oper}} \end{bmatrix} = \begin{bmatrix} F_1 & \cdots & F_n \\ \vdots & \ddots & \vdots \\ F_1 & \cdots & F_n \end{bmatrix}^{-1} \begin{bmatrix} \omega_{1}^{\text{oper}} \\ \vdots \\ \omega_{n}^{\text{oper}} \end{bmatrix} \]
Transfer Path Analysis Measurements - Loads

Direct Measured

Direct measured forces

Mount Stiffness

\[ F(\omega) = K(\omega)[X_s(\omega) - X_t(\omega)] \]

Single Path Inversion

Single Source – Multiple Indicator

Matrix Inversion

Multiple Source – Multiple Indicator

Simcenter OPAX

Multiple Source – Limited number of Indicator

Assume model => reduce indicators by identifying reduced set of model parameters
Transfer Path Analysis
Measurements Simcenter OPAX

\[ P(\omega) = \sum H_i(\omega) F_i(\text{parameters}, a_{ai}(\omega), a_{pi}(\omega)) \]

- Soft mounts
  \[ F_i(\omega) = K_i \frac{(a_{ai}(\omega) - a_{pi}(\omega))}{-\omega^2} \]
- Hard mounts
  \[ F_i(\omega) = K_i \frac{a_{ai}(\omega)}{-\omega^2} \]

(dis)advantages

- Limited set of FRFs required
- No disassembly into trimmed-body condition (depends on the expected accuracy)
- Limited body-information (compared to Matrix-Inversion)
Transfer Path Analysis
Measurements – Transfer functions – Removal of source

Operational condition

\[ y = F_1 \times FRF_1 + F_2 \times FRF_2 \]

FRF measurement without removing source

\[ y = F_1 \times FRF_1 + F_2 \times FRF_2 \]
- Only valid if \( F_2 \times FRF_2 \ll F_1 \times FRF_1 \)

Correct method for FRF measurement

\[ y = F_1 \times FRF_1 \]

Use only when:
- Coupling is weak between paths
- Able to hit at force location
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Strain-based load identification
Problem definition: Closely coupled paths example

Road Noise TPA:

- 72 paths/loads examined
- Some forces very close together

2 times 3 forces to be identified that are very close together
Strain-based load identification

Problem Definition: Matrix Inversion

Example TPA Result: Important Path Contributions

Interior Microphone

Seat Acceleration

Both Acceleration and Strain Based TPA provide a good quality target response synthesis

Measured Response
Calculated Response (Accel TPA)
Calculated Response (Strain TPA)
Strain-based load identification

Problem Definition: Matrix Inversion

Example TPA Result: Interior Noise

Peak in noise level resulting from Tire Cavity Mode

Example TPA Result: Important Path Contributions

Based on this quick **TPA acceleration result** evaluation:

- Path # 2 has an important contribution to the interior noise.
- Path # 2 high contribution level seems to be related to a high force level.

However, Path # 2 is the **vertical load** of the connection of a **lateral** suspension link to the body. Can this result be trusted?

Example TPA Result: set of identified Body Loads

Example TPA Result: set of identified Body Loads

‘Red Load’ – Load of Path 2
Even though the target synthesis is nearly identical for the 2 TPA methods, the identified loads however, are completely different.

Which load set is most reliable?
For a Lateral Link a high Y-dir load is expected, with low level loads in X-dir and Z-dir.
Strain-based load identification
Problem Definition: Matrix Inversion

Comparison and Analysis of 2 close-by forces in Z-direction

Acceleration TPA the 2 loads are in counter-phase over the full frequency range
Strain-based load identification
Problem Definition: Matrix Inversion
What is the problem?

\[ \{F(\omega)\} = [H(\omega)]^{-1} \cdot \{a(\omega)\} \]

Condition Number for an example structure with a high number of inputs

- Acceleration FRF Matrix Condition number is much higher as the Strain FRF Matrix Condition number
- Accurate load identification using the Acceleration FRF Matrix can be problematic
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Frequency domain TPA vs. Time domain TPA

Indicators (orders, spectra) → FRF, K → Frequency source model → Loads (orders, spectra) → NTF → Path contributions (orders, spectra)

Indicators (time traces) → FRF Filter → FRF Filter = FRF Filter → FRF Filter = FRF Filter → FRF Filter

Auralization, Signature Analysis, Sound Quality metrics ...
Frequency domain TPA vs. Time domain TPA

**Frequency Domain TPA**

- Order analysis
- Spectrum analysis
  - Run-up & run-down
  - Stationary: e.g. road noise

Analysis as a function of rpm/frequency

Component editing → Source and NTFs

Auralization → Not directly possible
Frequency domain TPA vs. Time domain TPA

**Frequency Domain TPA**
- Order analysis
- Spectrum analysis
  - Run-up & run-down
  - Stationary: e.g. road noise

Analysis as a function of rpm/frequency

Component editing ➔ Source and NTFs

Auralization ➔ Not directly possible

**Time Domain TPA**
- Time traces:
  - Run-up & run-down
  - Stationary: e.g. road noise
  - Transient: e.g. engine start-up
  - Semi-stationary: e.g. idle noise, frequency modulation …

Analysis as a function of time

Component editing ➔ Source and NTFs

Auralization ➔ Audio replay
Time-Domain TPA for PBN Instrumentation

\[ L = r \]

\[ y_k = \text{targets (measured & predicted)} \]

\[ \text{indicators (measured)} \]

\[ \text{sources (to be identified)} \]

\[ x = 0 \]

\[ x = - \]
Time-Domain TPA for PBN
Force / target response calculations

transmission
exhaust
engine
tire
Good match between measured I-PBN result and synthesized ASQ I-PBN result
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Blocked force/free velocity principle

1. Blocked Force

2. Free Velocity

\[ F_{2Bl} = H_{22}^{-1} A_{2Free} \]

Blocked force/free velocity is a property of the component independent of the environment it’s assembled in.
Converting Blocked Force (spring connection) to assembly connection forces

\[ \{F_{2r}\} = \{F_{3r}\} = [H_{22}^A + H_{33}^B + K^{-1}]^{-1} \times [H_{22}^A] \times \{F_{2bl}\} \]

\[ \{F_{2r}\} = \{F_{3r}\} = [H_{22}^A + H_{33}^B + K^{-1}]^{-1} \times \{v_{2free}^A\} \]
Example Applications
Steering System

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<td>Body FEM/TEST FRF</td>
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**Invariant Source Load (TEST)**

A

\[
\begin{align*}
\{F^A_{bl}\} &= \left[H^C_{i1}\right]^{-1} \cdot \{a^C_i\} \\
\{a^C_i\} &\text{ bench} \quad \times \\
\end{align*}
\]

B

\[
\begin{align*}
\{F^A_{bl}\} \quad &\rightarrow \\
\{F_r\} \quad &\rightarrow \\
p = \left[H^B_{32}\right] \cdot \{F_r\}
\end{align*}
\]

\[
\{F_r\} = \left[H^A_{11} + H^B_{22} + K^{-1}\right]^{-1} \cdot \left[H^A_{11}\right] \cdot \{F^A_{bl}\}
\]

**Full System Transfer Function**
Example Applications
Road Noise - Tire

Source Mechanism

Invariant Source Load (TEST)

Example: Invariance of wheel center blocked force: Strongly coupled system & coupled to very different vehicles
Concept: Component Based TPA
Test components and virtual assemble components

Benefits:
• Can try out different car variants before there is a prototype.
• Can use this technique for component target setting ➔ Less surprises when assembling the vehicle.
• Can find out worst case combination and limit validation/testing to this configuration ➔ Intelligent reduced testing
Thank You

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