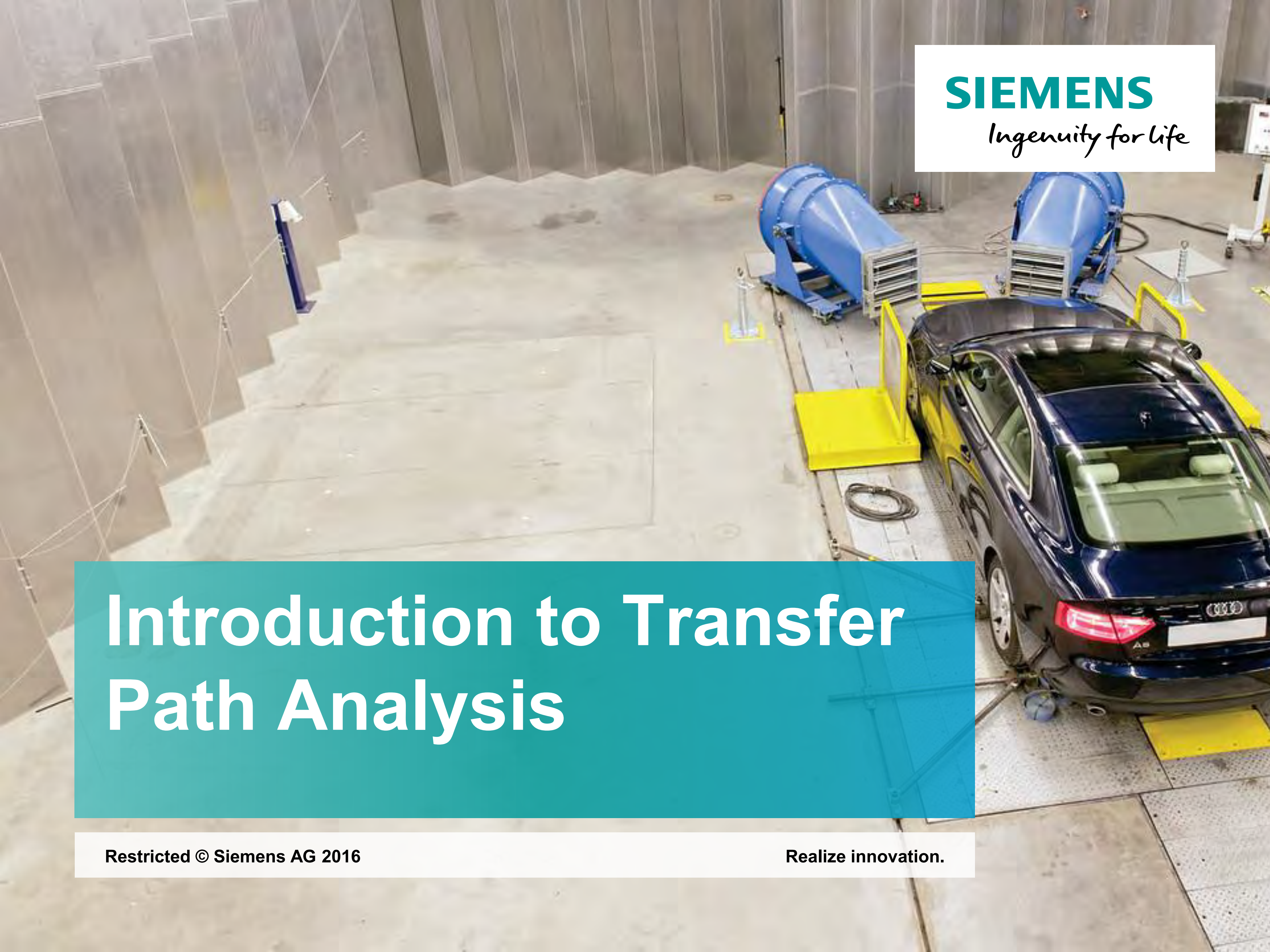

Introduction to Transfer Path Analysis

Realize innovation.

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

SIEMENS

1 • What is TPA ?

2 • Practical considerations

3 • Strain TPA

4 • Time TPA

5 • Component TPA

Transfer path analysis for mechanical industry
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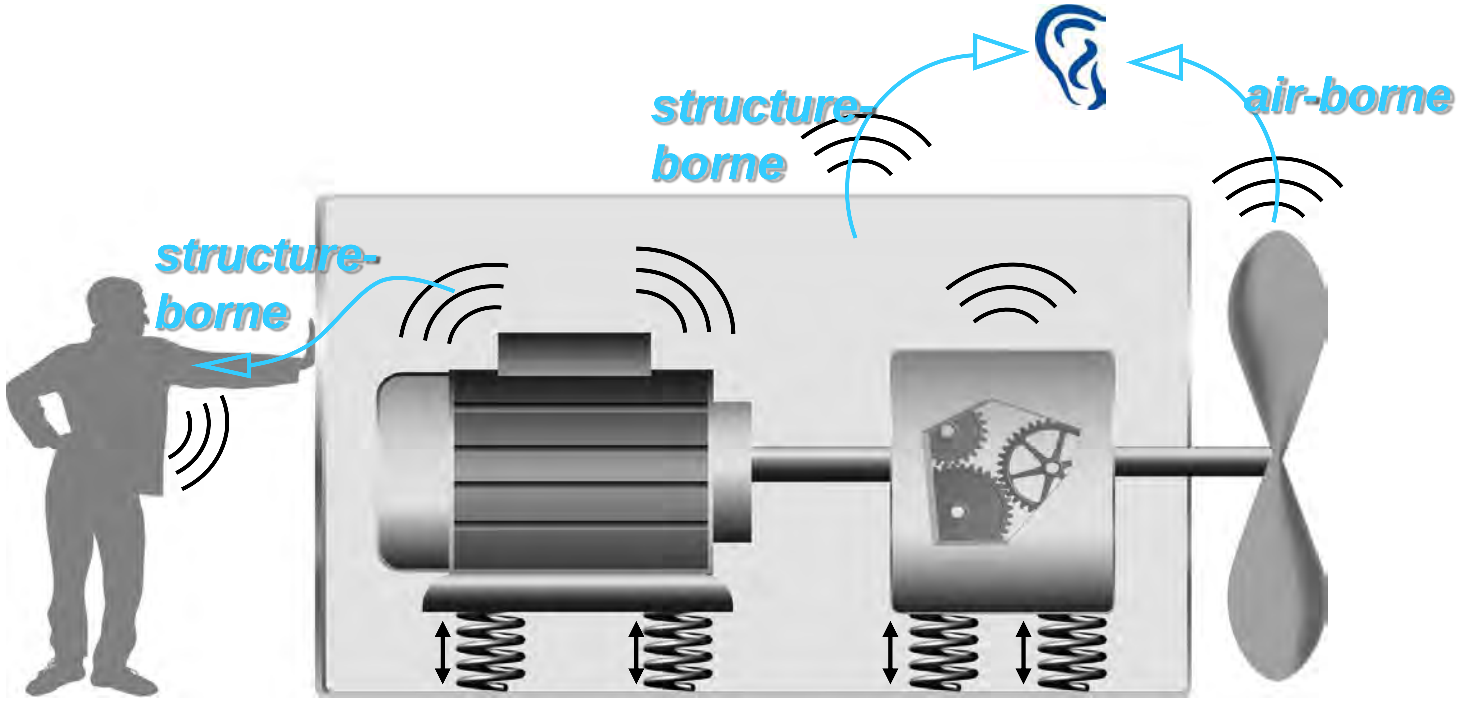
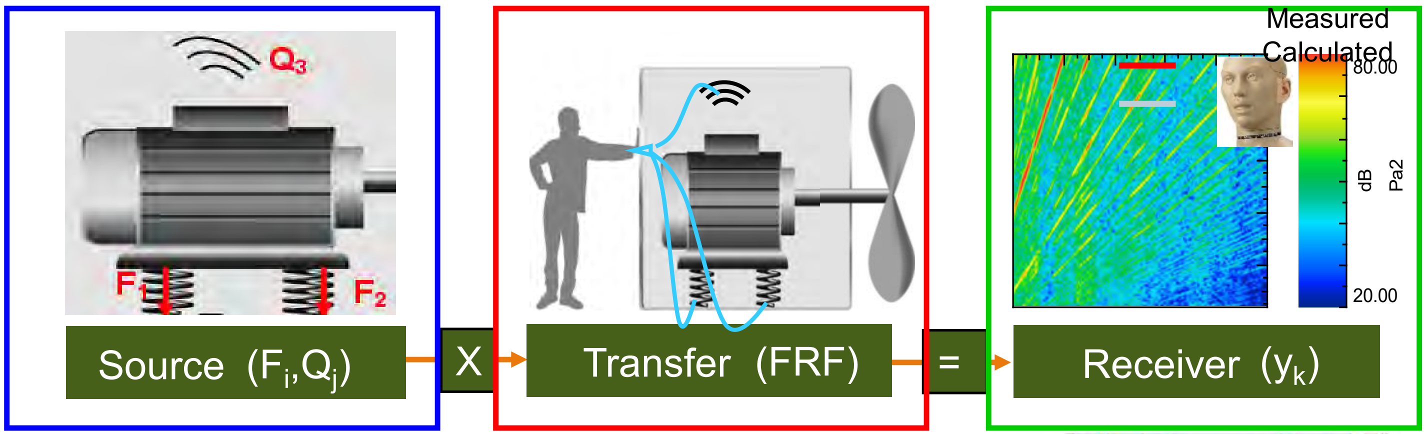


- Transfer path analysis quantifies and visualizes the strengths of selected sources and their contribution via multiple transmission paths to a selected receiver signal

Transfer Path Analysis

Source-transfer-receiver approach

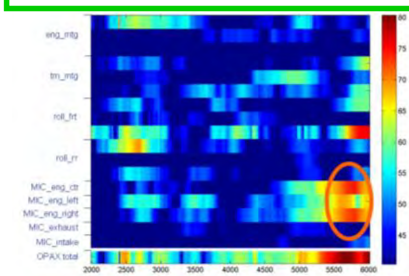
SIEMENS



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

= structural

= airborne



Most time spent during a TPA is on measuring:

- Fi and Qj during operation
- FRF functions correctly

Transfer Path Analysis
Step 1: Which path is contributing?

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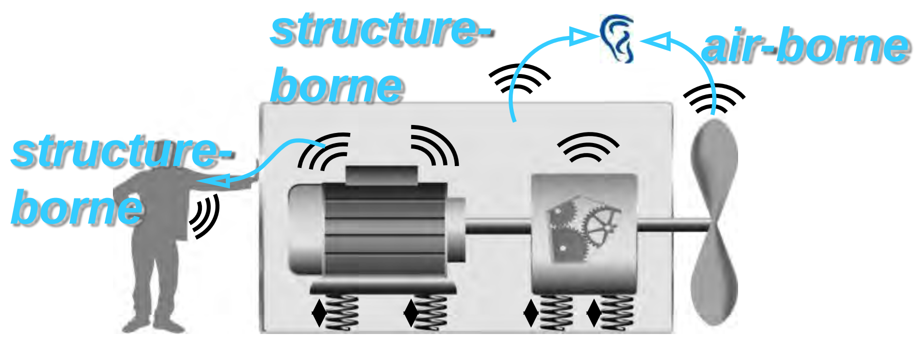
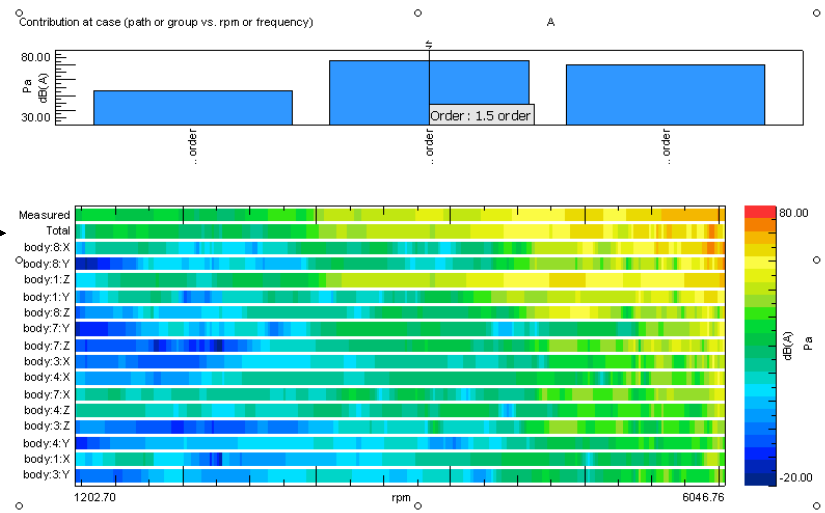
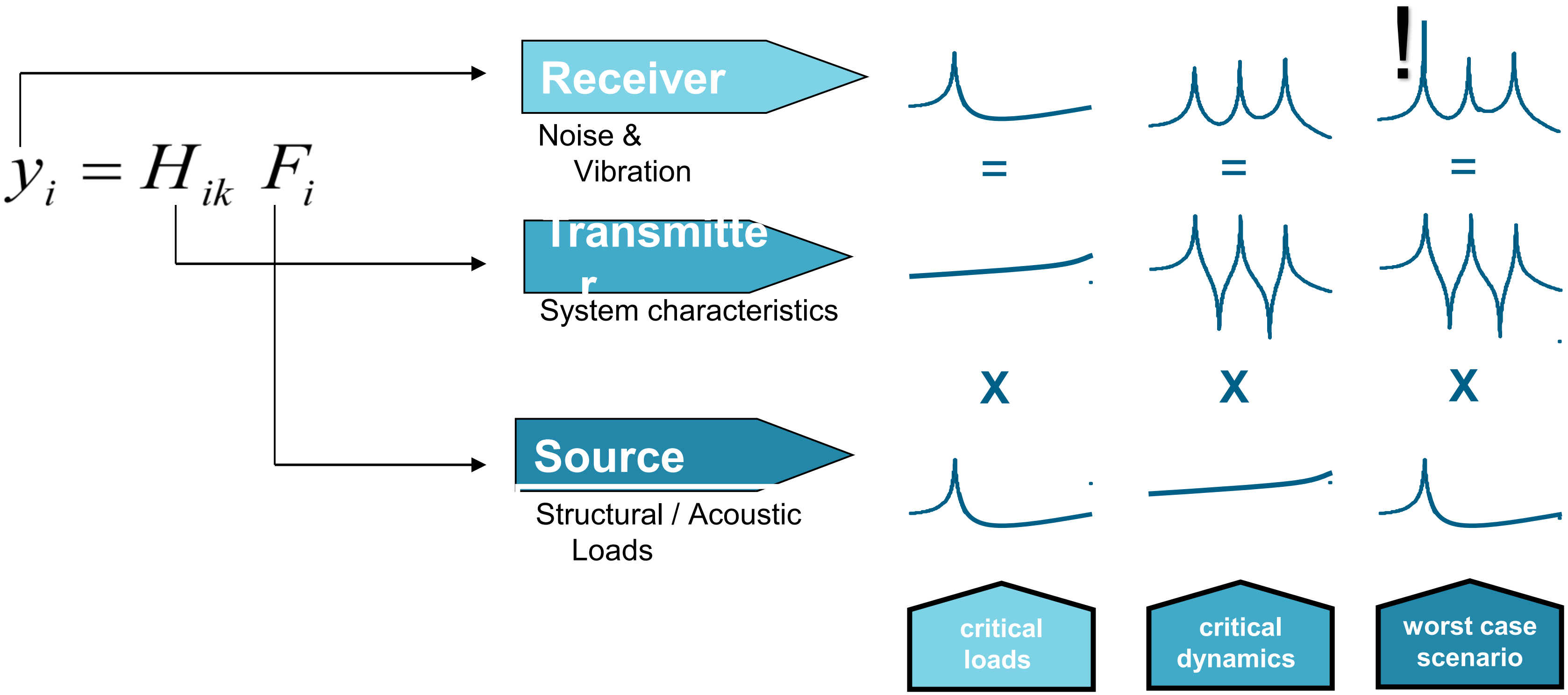
$$y_k = \sum_{i=1}^{n} y_i$$

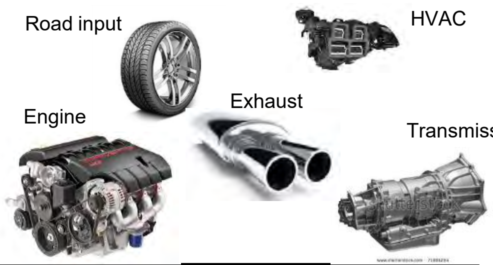


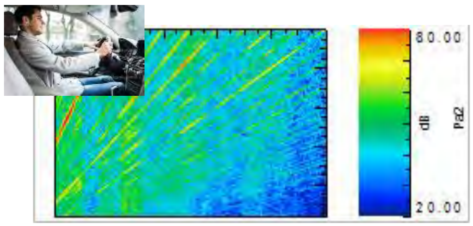


Transfer Path Analysis
Step 2: Why is path contributing?



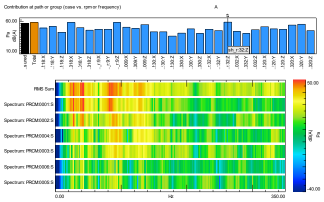
System Engineering for NVH
Source-transfer-receiver model

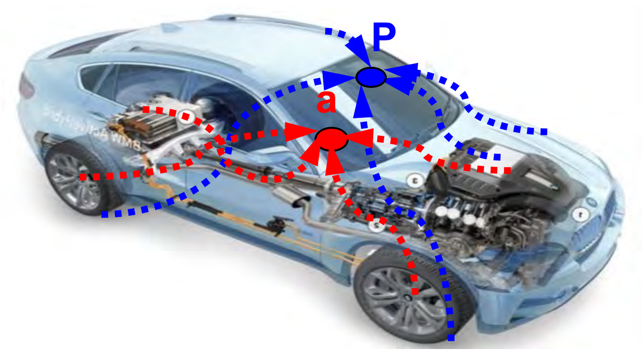




Source X Transfer = Receiver

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





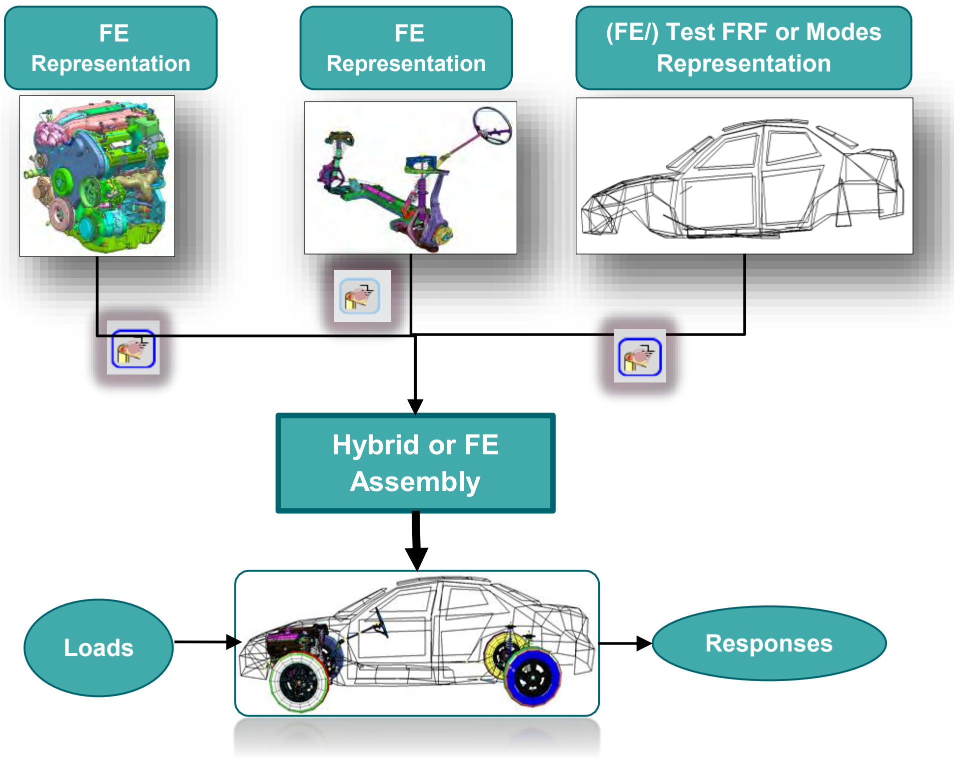
$$y_k = \underbrace{\sum_{i=1}^{n} FRF_{ik} * F_i}_{=\ \text{structural}} + \underbrace{\sum_{j=1}^{p} FRF_{jk} * Q_j}_{=\ \text{airborne}}$$

Hybrid Modeling – Example
Engine Noise inside Cabin

SIEMENS

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)

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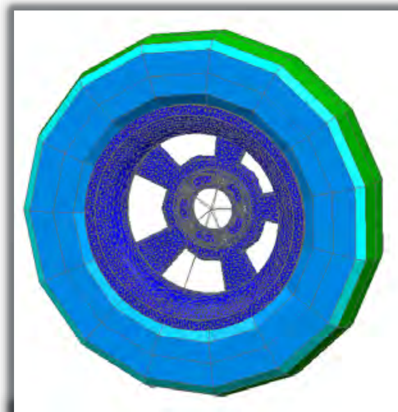
- Test Tire Component
- Equivalent model of a damper
- FE models of Subframe, Suspension Arms, Knuckle, Strut and Brake

(Courtesy: A Hybrid Full Vehicle Model for Structure Borne Road Noise Prediction – SAE Paper 2005-01-2467)

Focus → Modeling accuracy



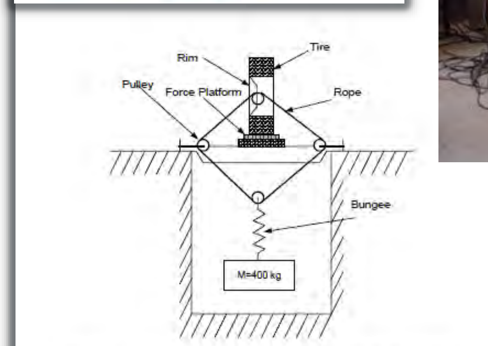
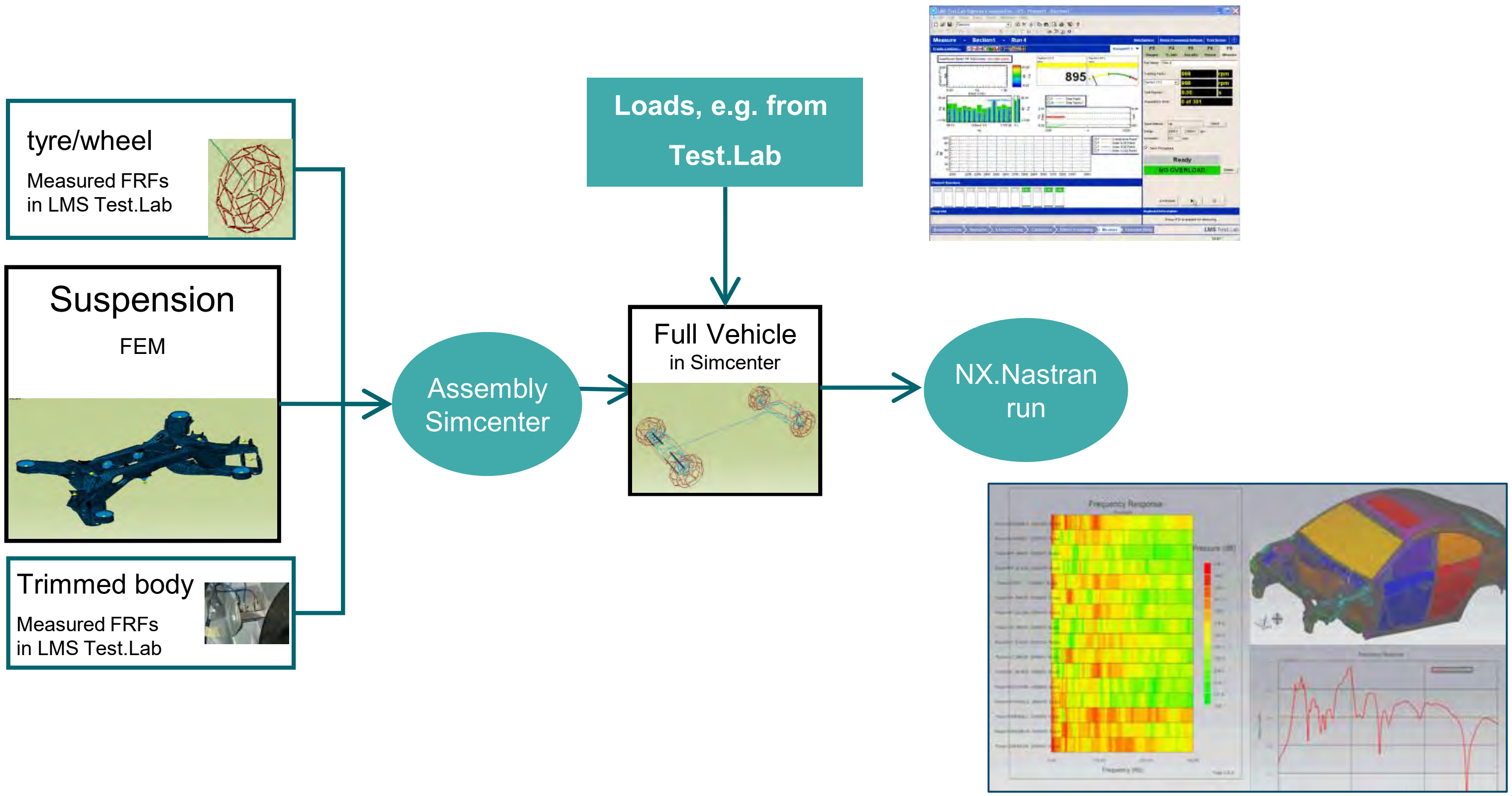


Figure 6 – Experimental tire set-up in pre-loaded condition

Damping Test Rig

Hybrid Full Vehicle Road Noise Evaluation (Simcenter and NX Nastran)



NVH Results –
Post-processing in Simcenter Noise and Vibration Modeling

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Insight

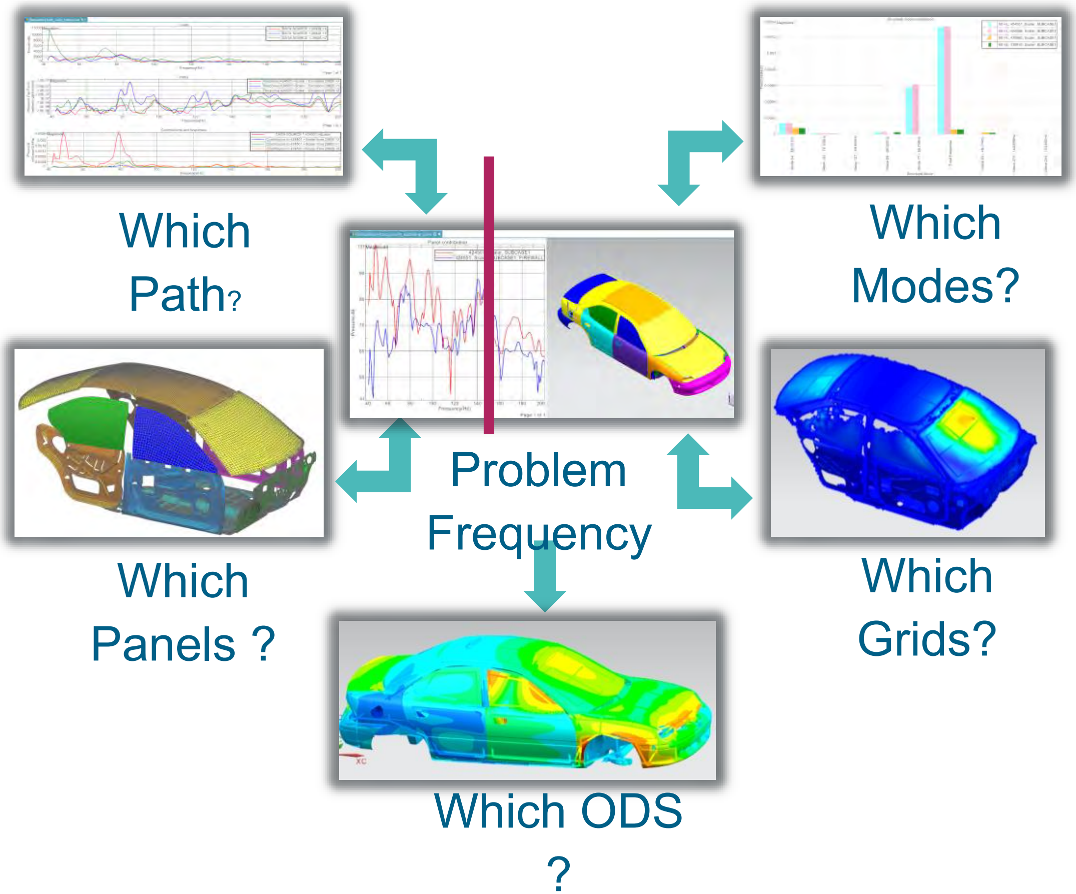
- Identify the problem

Contributions

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

Understanding Response

- Operational Deflection Shapes
- Equivalent Radiated Power



Transfer Path Analysis
What needs to be measured?

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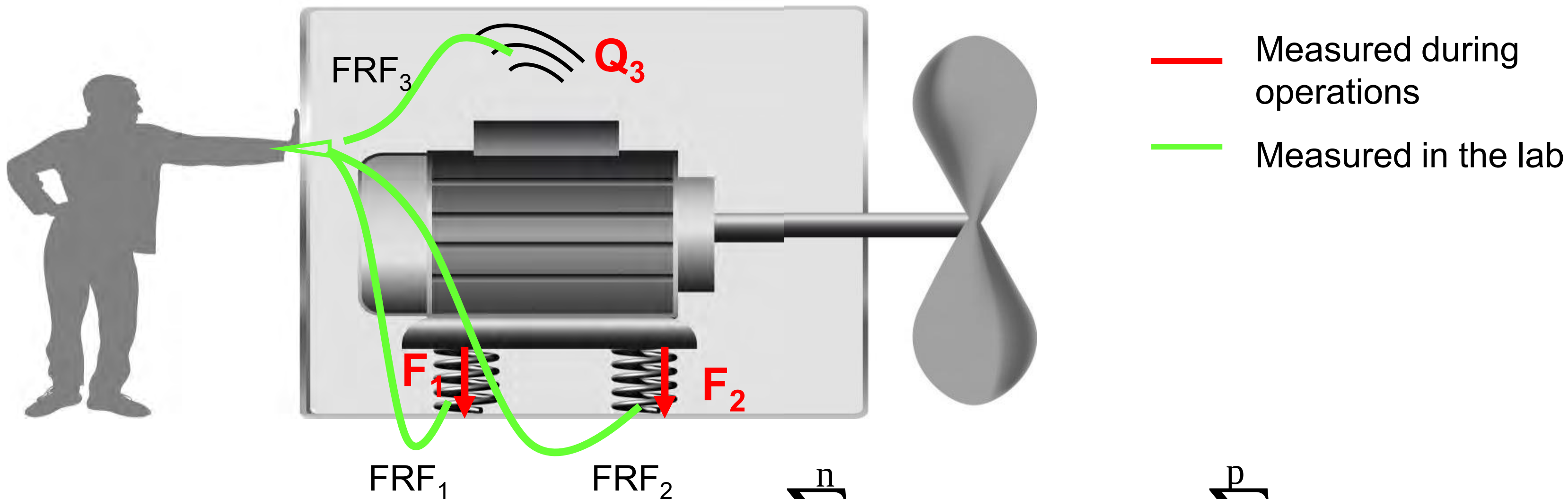


$$y_k = \sum_{i=1}^{n} NTF_{ik} * F_i + \sum_{j=1}^{p} NTF_{jk} * Q_j$$

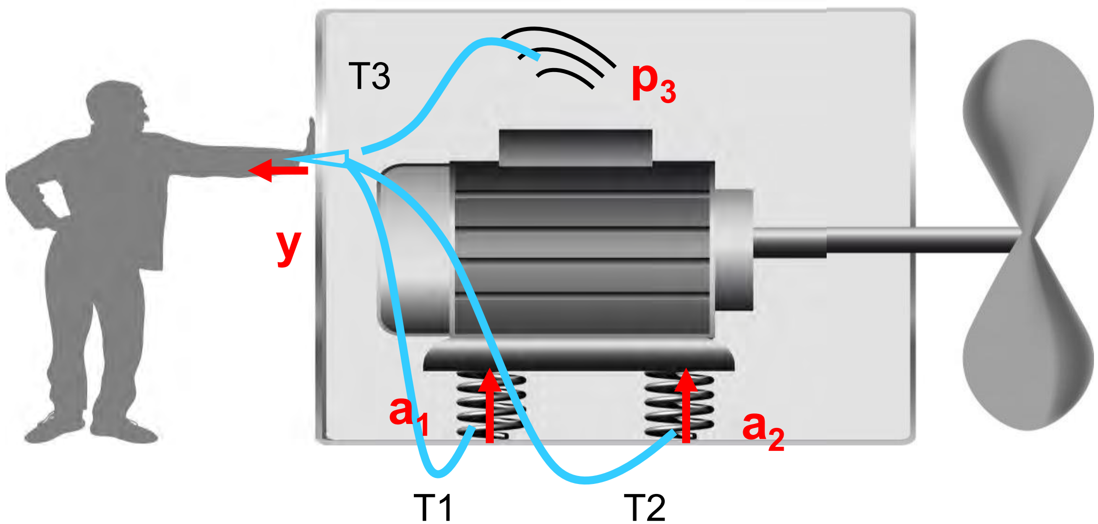
During operations:

- 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:

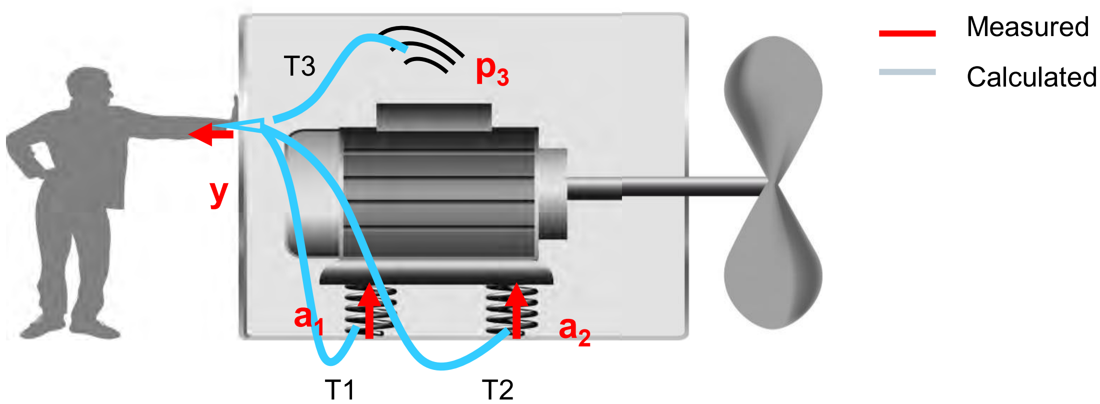
- Accelerations at the force locations
- Pressures at the Acoustical sources
- Target locations

Fast method, takes ±1 day of measurements

- Transmissibility method

$$y_k = \underbrace{\sum_{i=1}^{n} T_{ik} * a_i}_{\text{structural}} + \underbrace{\sum_{j=1}^{p} T_{jk} * p_j}_{\text{airborne}}$$

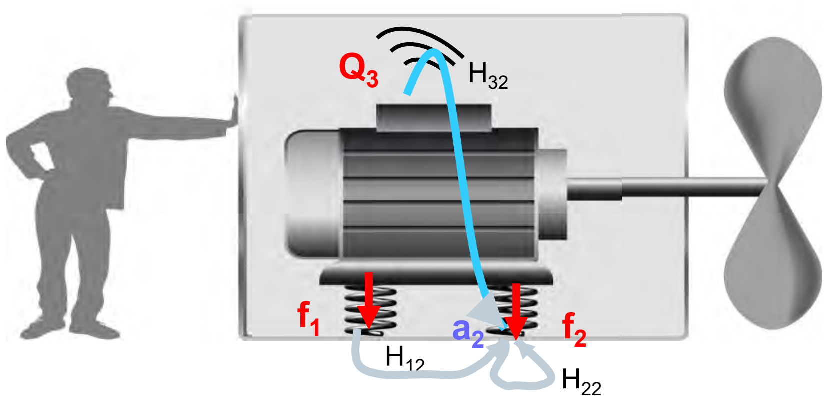
OPA method:
Potential problems for wrong results: cross-coupling



$$y = T_1\ a_1 + T_2\ a_2 + T_3\ p_3$$

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.

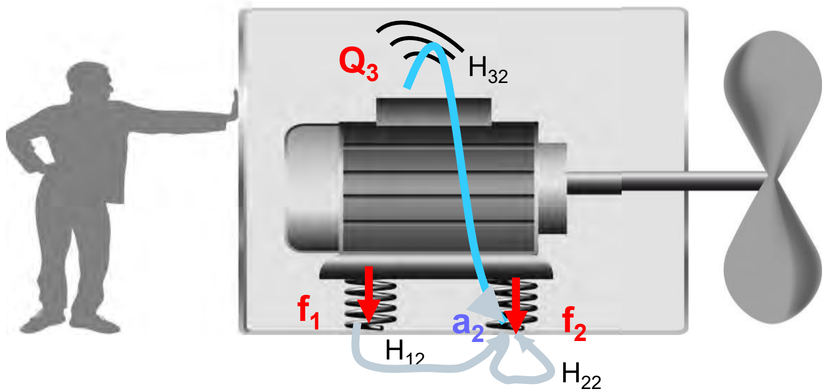
$$a_2 = H_{12}.f_1 + H_{22}.f_2 + H_{32}.Q_3$$

Normally

$$H_{22}f_2 >> H_{12}.f_1 + H_{32}.Q_3$$

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

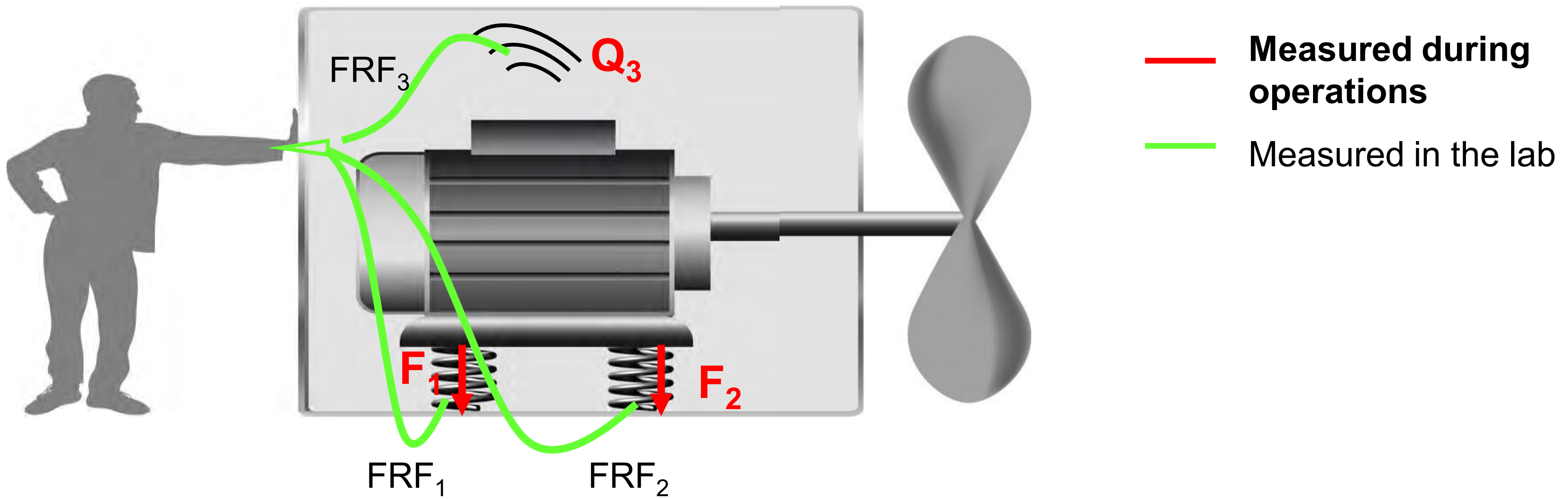
$$T_2\ a_2 > T_1\ a_1\ and\ \ T_2\ a_2 > T_3\ p_3\ due\ \ force\ at\ \ f_1$$

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

SIEMENS

1. What is TPA ?
2. Practical considerations
3. Strain TPA
4. Time TPA
5. Component TPA

Transfer Path Analysis
Operational measurements



During operations:

- Forces going into the structure, requires in general quiet some measurements
- Acoustical sources
- Target locations

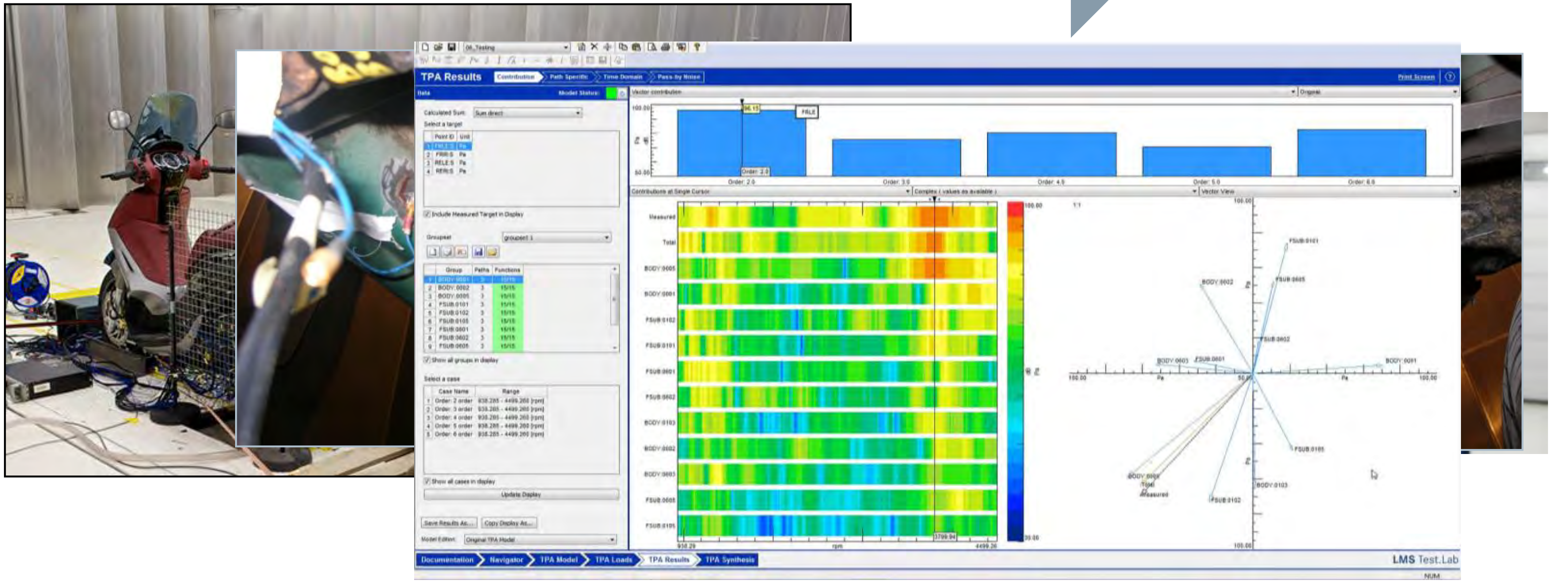
In the lab: measurement of the FRF, is also a tedious job

In general, TPA is a measurement intensive application

Test Based TPA
Process Overview

SIEMENS

- Step 1: Preparation
- Step 2: Operational Measurements
- Step 3: FRF Measurements
- Step 4: TPA



Transfer Path Analysis:
Requirements: One integrated process

SIEMENS

EASY & PRODUCTIVE

COMPLETE

INSIGHT

CONVINCE & INNOVATE

PARTNER

Step 1: Preparation

Step 2: Operational Measurements

Step 3: FRF Measurements

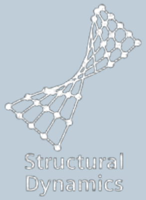
Signature Testing

Impact Testing

MIMO FRF Testing

MIMO Sine Testing

Excitation Hardware: Simcenter QSources



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

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INSIGHT

CONVINCE & INNOVATE

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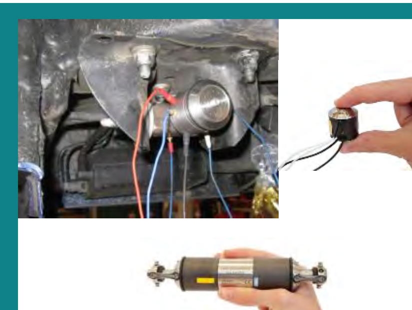
Reciprocal FRF excitation hardware

- ✓ 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

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Step 4: TPA

Load Estimation Methods

Direct Measured

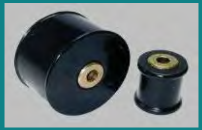
Mount Stiffness

Single Path Inversion
Single Source –
Multiple Indicator

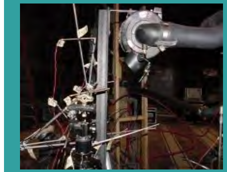
Matrix Inversion
Multiple Source –
Multiple Indicator

Simcenter OPAX
Multiple Source –

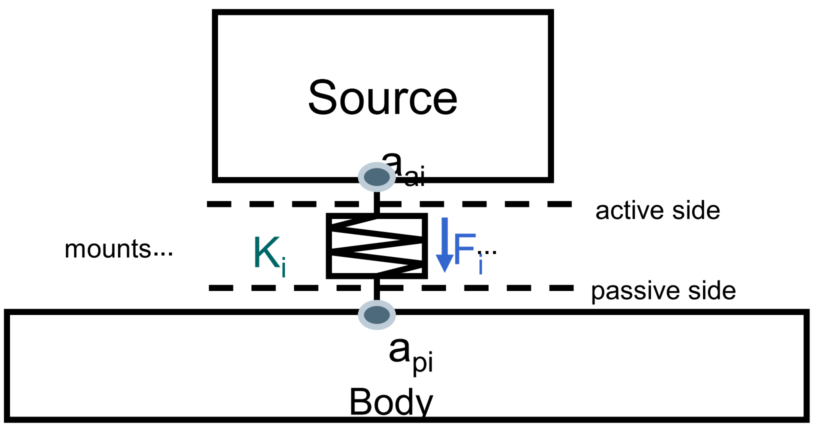
Structural



Airborne



Transfer Path Analysis
Load identification: mount stiffness method



operational accelerations at both sides of mount

||

$$F_i(\omega) = K_i(\omega) * \frac{(a_{ai}(\omega) - a_{pi}(\omega))}{-\omega^2}$$

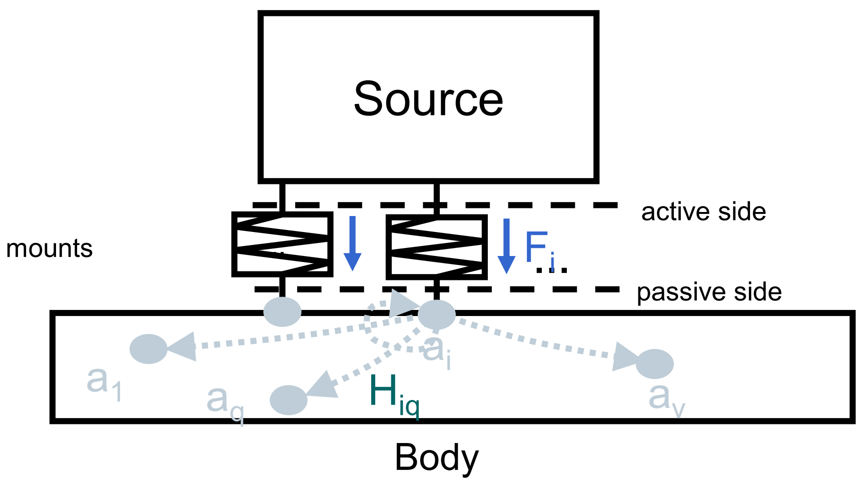
|| operational FORCES

|| mount stiffness

Transfer Path Analysis

Load identification: matrix inversion method

SIEMENS



FRF matrix

||

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

|| operational forces

|| indicator accelerations

Structural

Direct Measured *Direct measured forces*

Mount Stiffness

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

Single Path Inversion

Single Source –
Multiple Indicator

$$F_1^{oper} = \begin{bmatrix} \dfrac{\ddot{x}_1}{F_1} \\ \dfrac{\ddot{x}_{1001}}{F_1} \\ \dfrac{\ddot{x}_{1002}}{F_1} \end{bmatrix}^{-1} \begin{bmatrix} \ddot{x}_1^{oper} \\ \ddot{x}_{1001}^{oper} \\ \ddot{x}_{1002}^{oper} \end{bmatrix}$$

Matrix Inversion

Multiple Source –
Multiple Indicator

$$\begin{bmatrix} F_1^{oper} \\ \ldots \\ F_n^{oper} \end{bmatrix} = \begin{bmatrix} \dfrac{\ddot{x}_1}{F_1} & \ldots & \dfrac{\ddot{x}_1}{F_n} \\ \ldots & \ldots & \ldots \\ \dfrac{\ddot{x}_m}{F_1} & \ldots & \dfrac{\ddot{x}_m}{F_n} \end{bmatrix}^{-1} \begin{bmatrix} \ddot{x}_1^{oper} \\ \ldots \\ \ddot{x}_m^{oper} \end{bmatrix}$$

Transfer Path Analysis
Measurements - Loads

Structural

Direct Measured *Direct measured forces*

Mount Stiffness

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

Single Path Inversion

Single Source –
Multiple Indicator

$$F_1^{oper}=\begin{bmatrix}\frac{\ddot{x}_1}{F_1}\\ \frac{\ddot{x}_{1001}}{F_1}\\ \frac{\ddot{x}_{1002}}{F_1}\end{bmatrix}^{-1}\begin{bmatrix}\ddot{x}_1^{oper}\\ \ddot{x}_{1001}^{oper}\\ \ddot{x}_{1002}^{oper}\end{bmatrix}$$

Matrix Inversion

Multiple Source –
Multiple Indicator

$$\begin{bmatrix}F_1^{oper}\\ \cdots\\ F_n^{oper}\end{bmatrix}=\begin{bmatrix}\frac{\ddot{x}_1}{F_1} & \cdots & \frac{\ddot{x}_1}{F_n}\\ \cdots & \cdots & \cdots\\ \frac{\ddot{x}_m}{F_1} & \cdots & \frac{\ddot{x}_m}{F_n}\end{bmatrix}^{-1}\begin{bmatrix}\ddot{x}_1^{oper}\\ \cdots\\ \ddot{x}_m^{oper}\end{bmatrix}$$

Simcenter OPAX

Multiple Source –
Limited number of Indicator

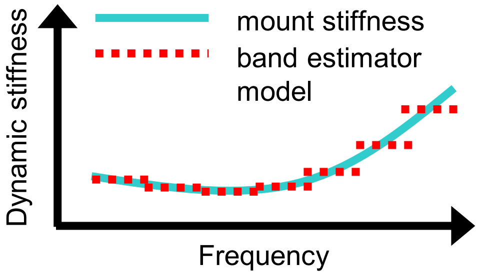
Assume model => reduce indicators by identifying reduced set of model parameters

Transfer Path Analysis
Measurements Simcenter OPAX

SIEMENS

$$P(\omega) = \sum H_i(\omega) F_i\left(parameters, a_{ai}(\omega), a_{pi}(\omega)\right)$$

- Soft mounts $F_i(\omega) = K_i \dfrac{\left(a_{ai}(\omega) - a_{pi}(\omega)\right)}{-\omega^2}$
- Hard mounts $F_i(\omega) = K_i \dfrac{a_{ai}(\omega)}{-\omega^2}$



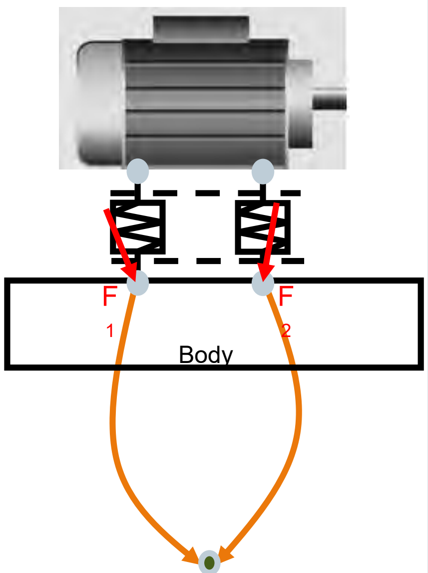
(dis)advantages

- 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

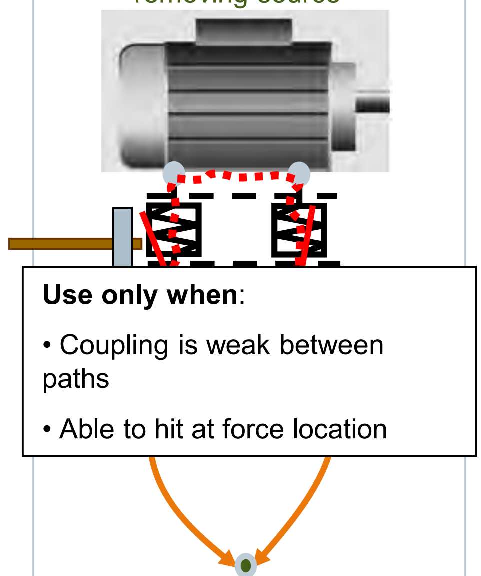
Measurements – Transfer functions – Removal of source

Operational condition



$y = F_1 \times FRF_1 + F_2 \times FRF_2$

FRF measurement without removing source



Use only when:

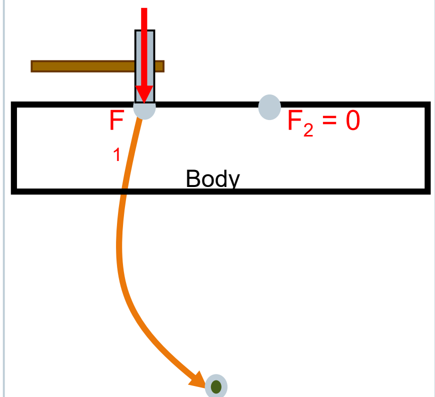
- Coupling is weak between paths
- Able to hit at force location

$y = F_1 \times FRF_1 + F_{2'} \times FRF_2$

- Only valid if

$F_{2'} \times FRF_2 << F_1 \times FRF_1$

Correct method for FRF measurement



$y = F_1 \times FRF_1$

Demo

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

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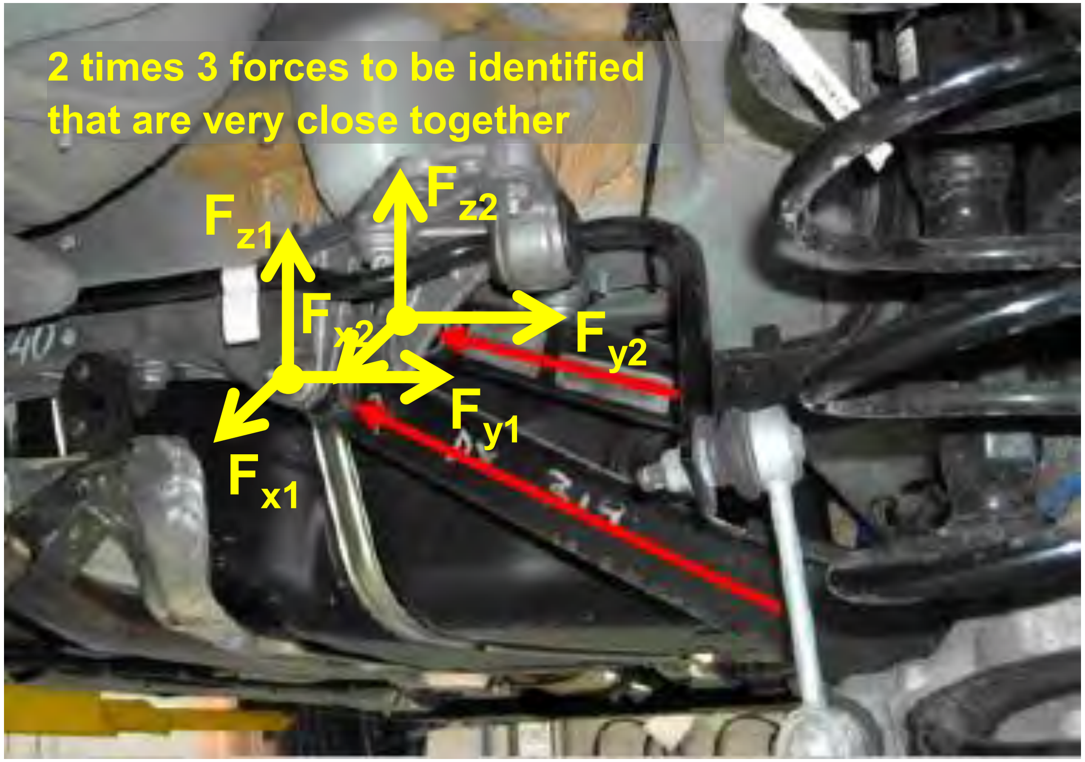
Strain-based load identification
Problem definition: Closely coupled paths example

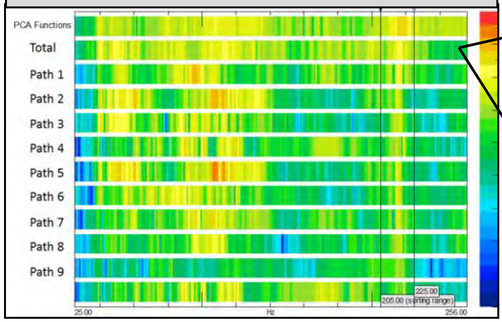
Road Noise TPA:

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

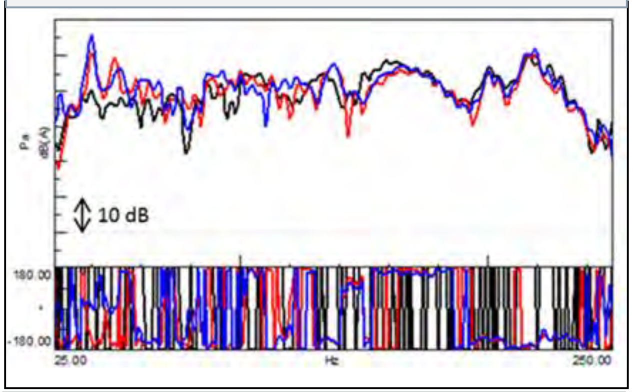


Strain-based load identification
Problem Definition: Matrix Inversion

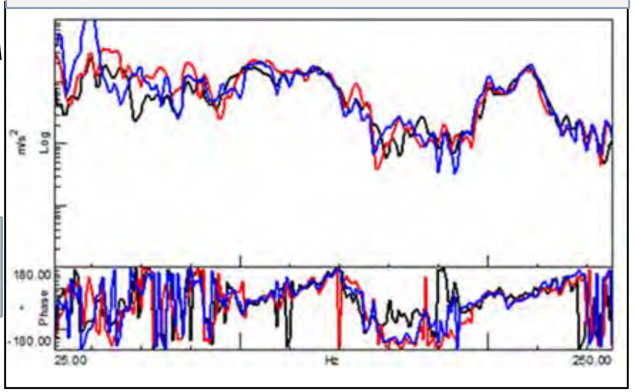
Example TPA Result: Important Path
Contributions



Interior Microphone



Seat Acceleration

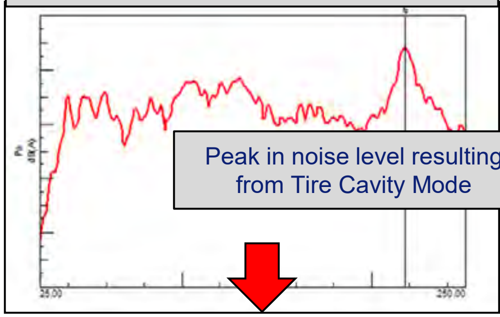


Measured Response
Calculated Response (Accel TPA)
Calculated Response (Strain TPA)

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

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**

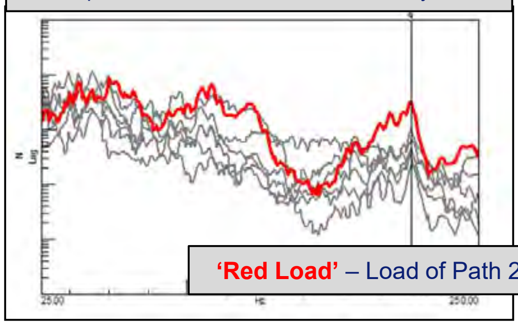
Based on this quick **TPA acceleration result** evaluation

→ Path # 2 has an important contribution to the interior noise

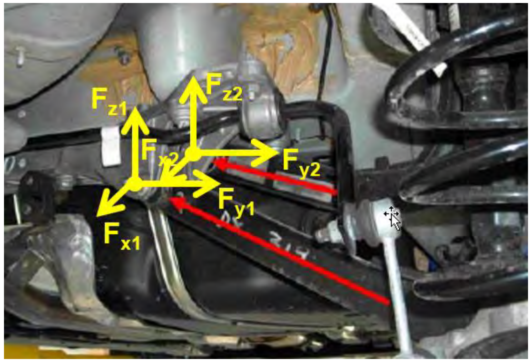
→ Path # 2 high contribution level seems to be related to a high force level

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 Lads



'Red Load' – Load of Path 2



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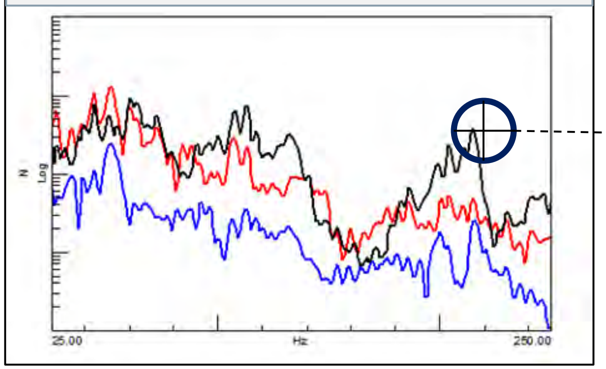
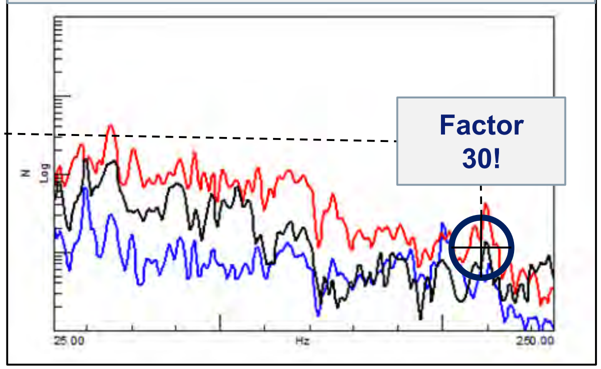
Acc. based Loads for a Lateral Suspension Link



Strain based Loads for a Lateral Suspension Link



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.

Body Load in X-direction
Body Load in Y-direction
Body Load in Z-direction

Mercedes-Benz

Strain-based load identification
Problem Definition: Matrix Inversion

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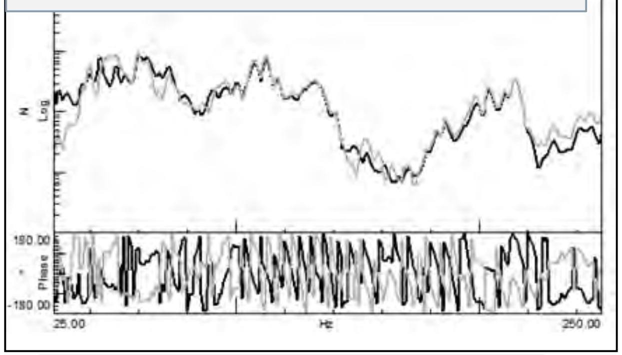
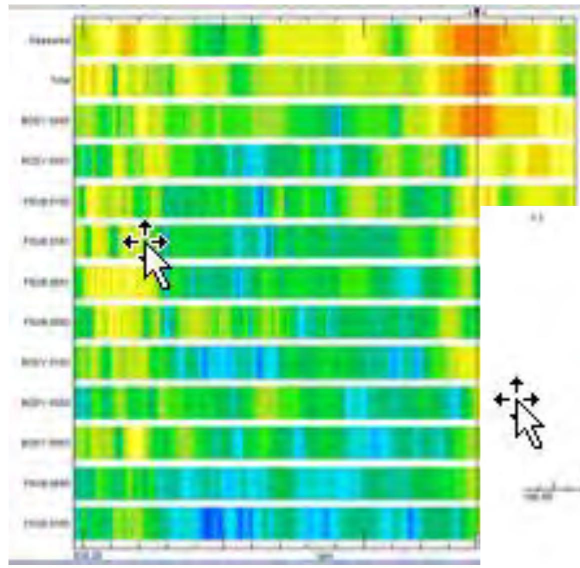
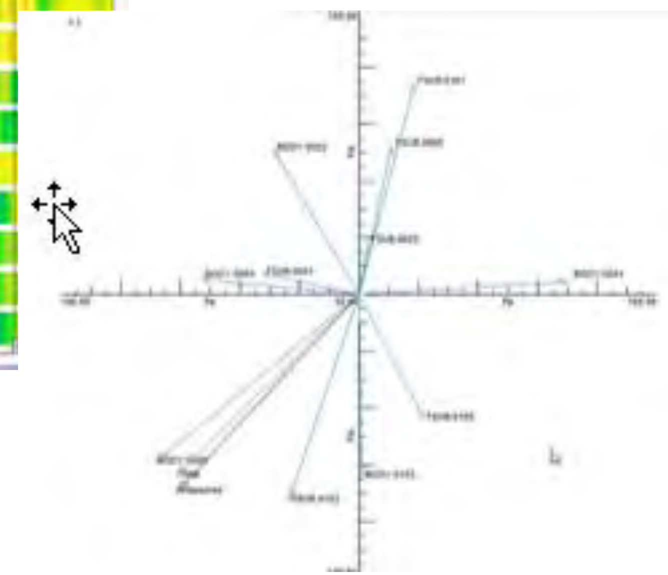
Comparison and Analysis of 2 close-by forces in Z-direction



Acceleration TPA the 2 loads are in **counter-phase** over the full frequency range



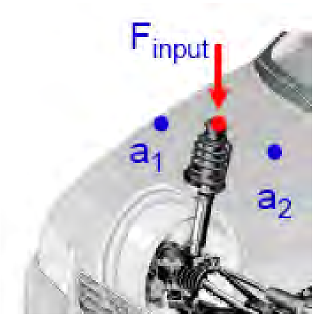


Mercedes-Benz

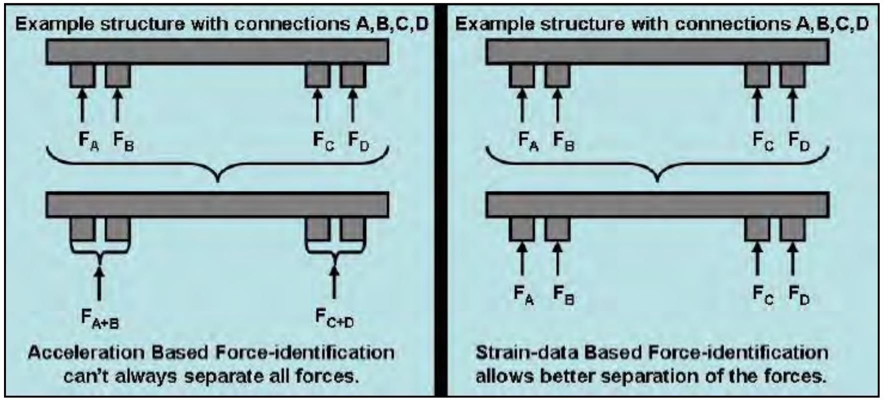
Strain-based load identification

Problem Definition: Matrix Inversion

What is the problem?



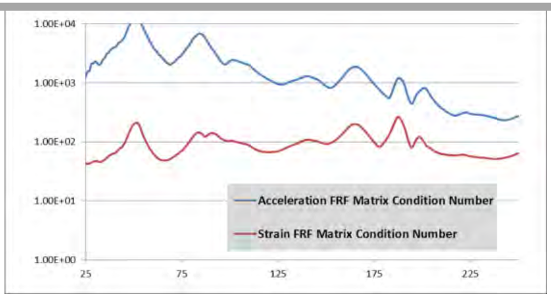
$$\{F(\omega)\} = [H(\omega)]^{-1} \cdot \{a(\omega)\}$$



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



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

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1	• What is TPA ?
2	• Practical considerations
3	• Strain TPA
4	• Time TPA
5	• Component TPA

Frequency domain TPA vs. Time domain TPA

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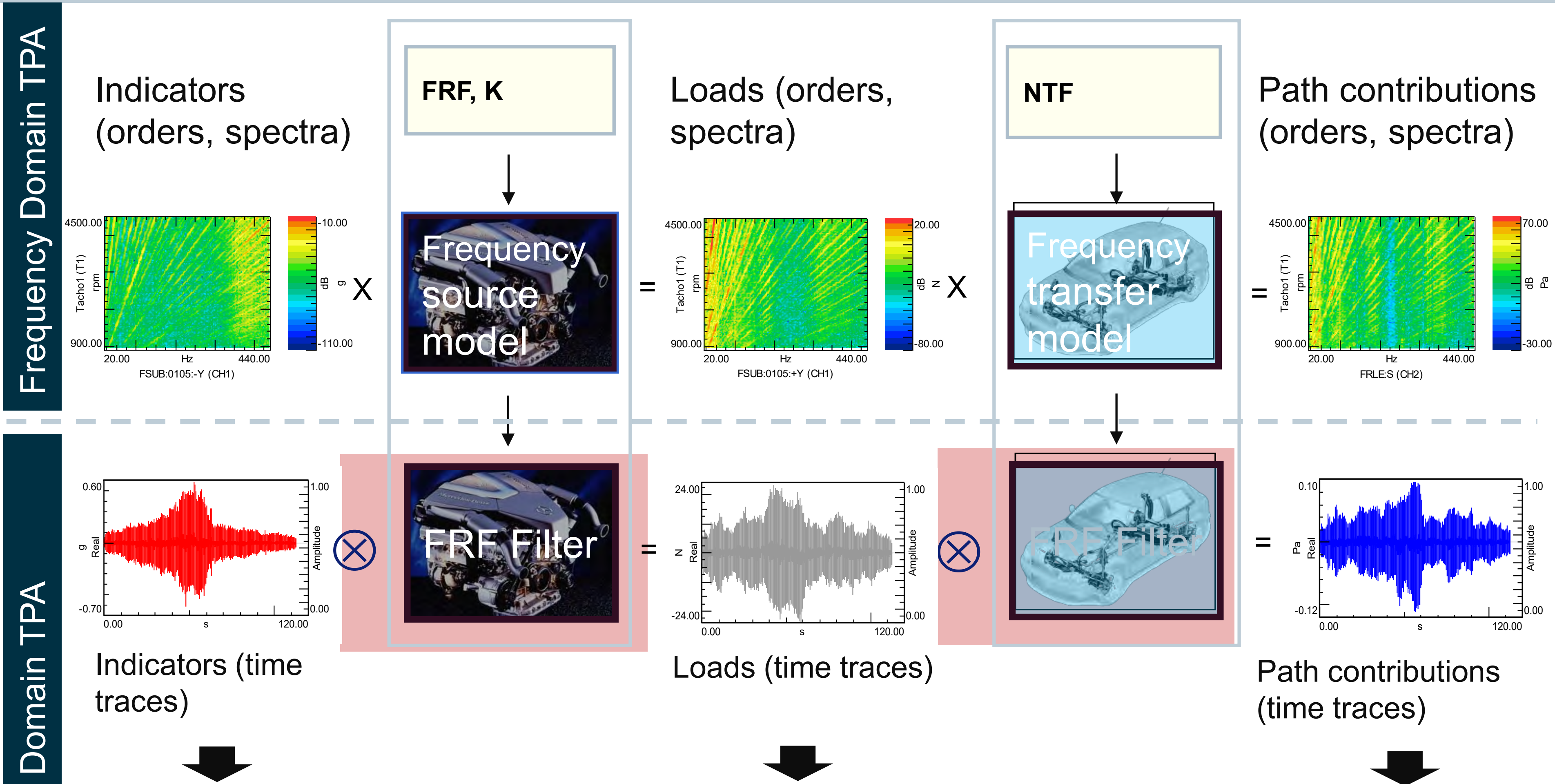


Auralization, Signature Analysis, Sound Quality metrics ...

Frequency domain TPA vs. Time domain TPA

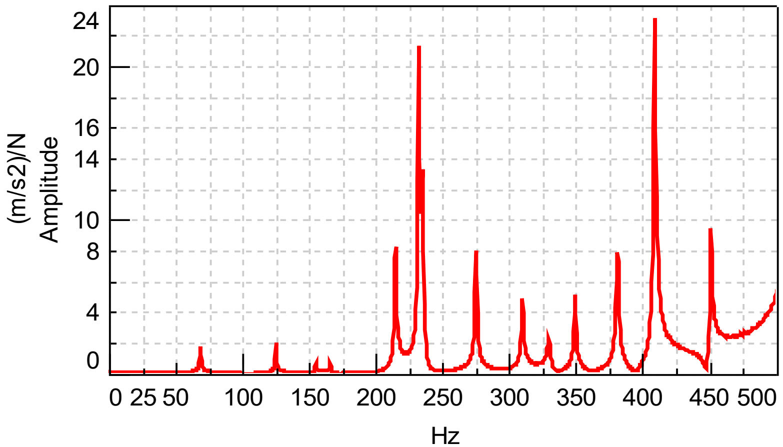
Frequency Domain TPA

- ➔ 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

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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

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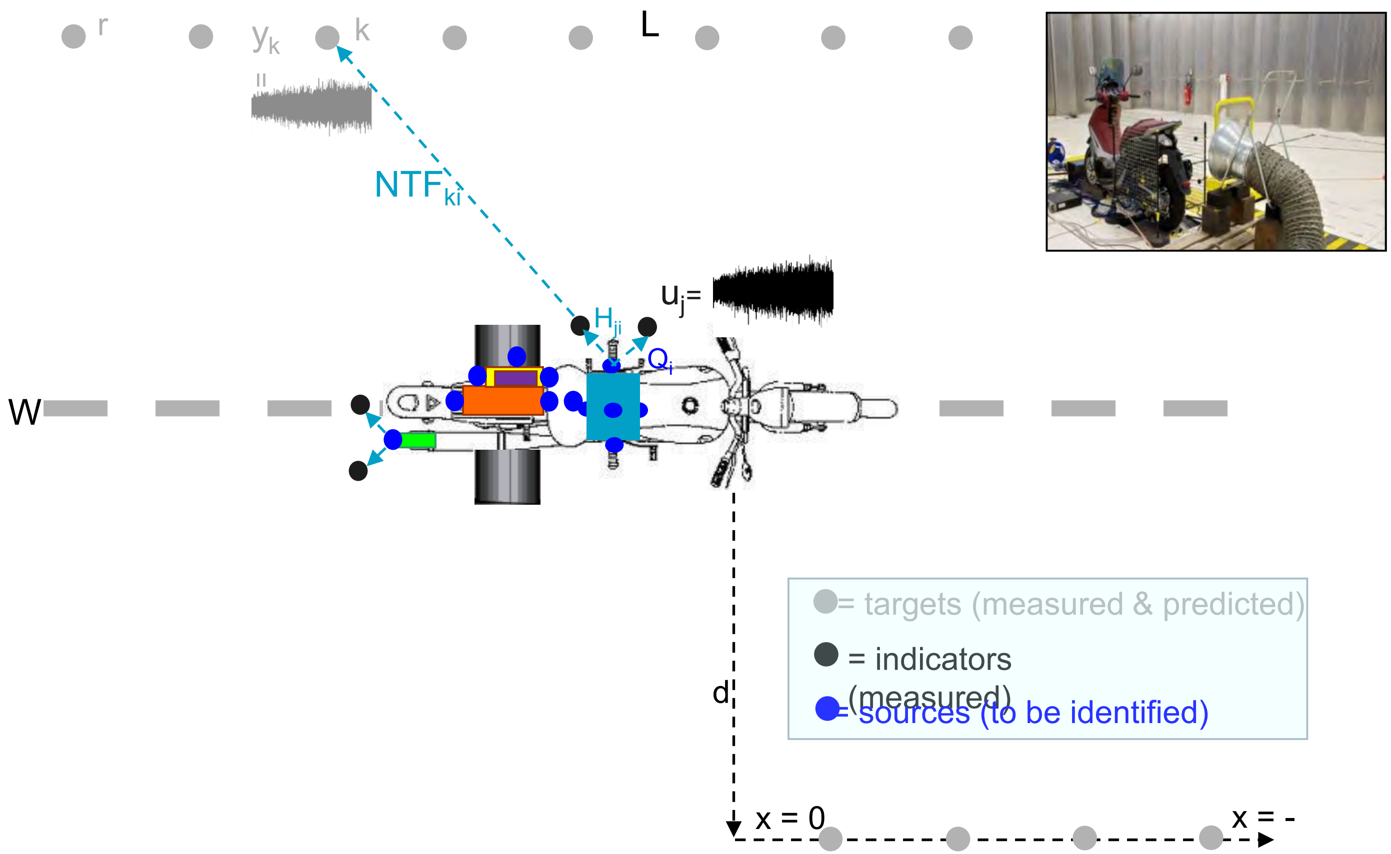

Time-Domain TPA for PBN
Force / target response calculations

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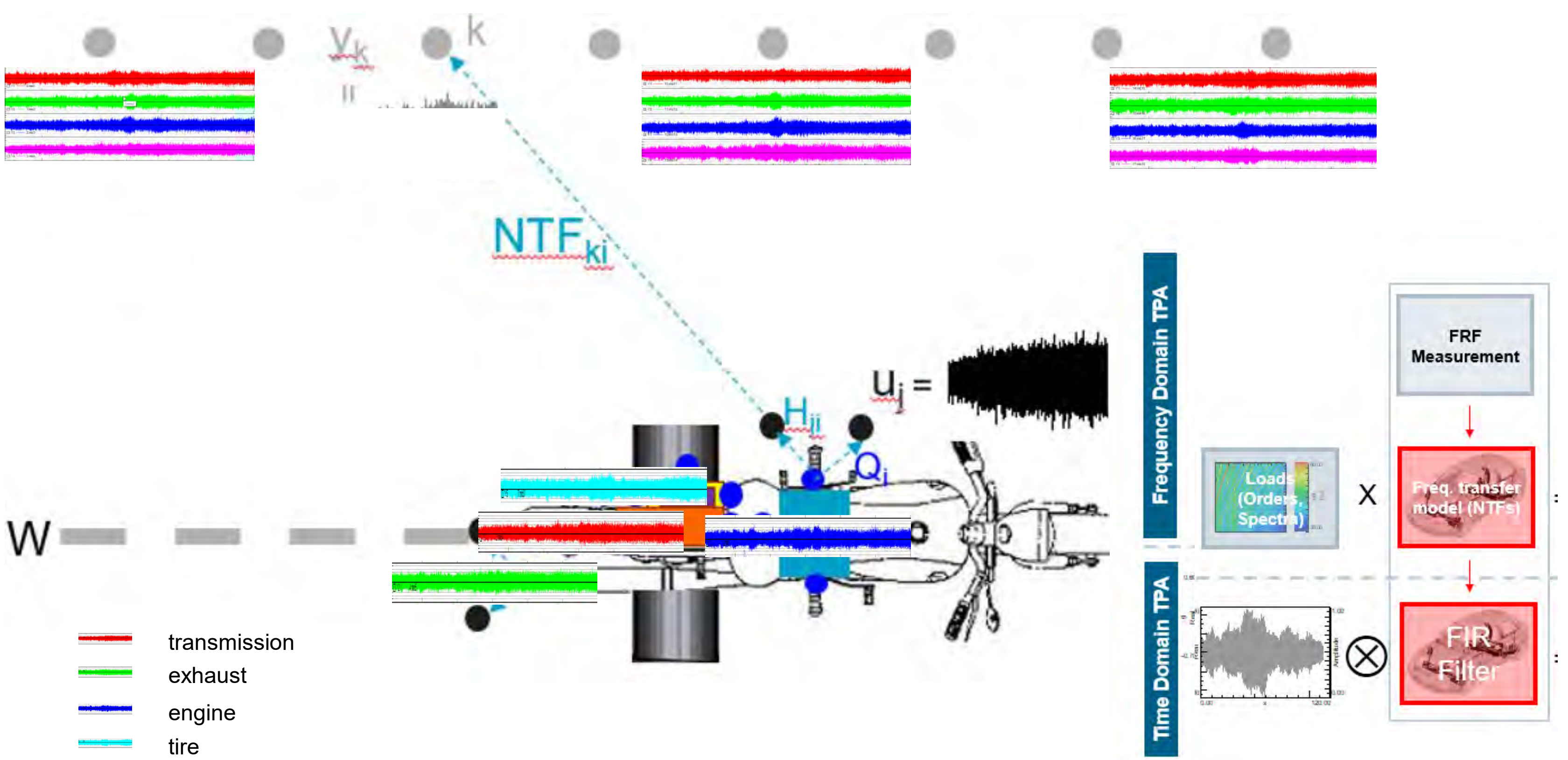

Time-Domain TPA for PBN
PBN Contribution Analysis – Example in 3rd gear

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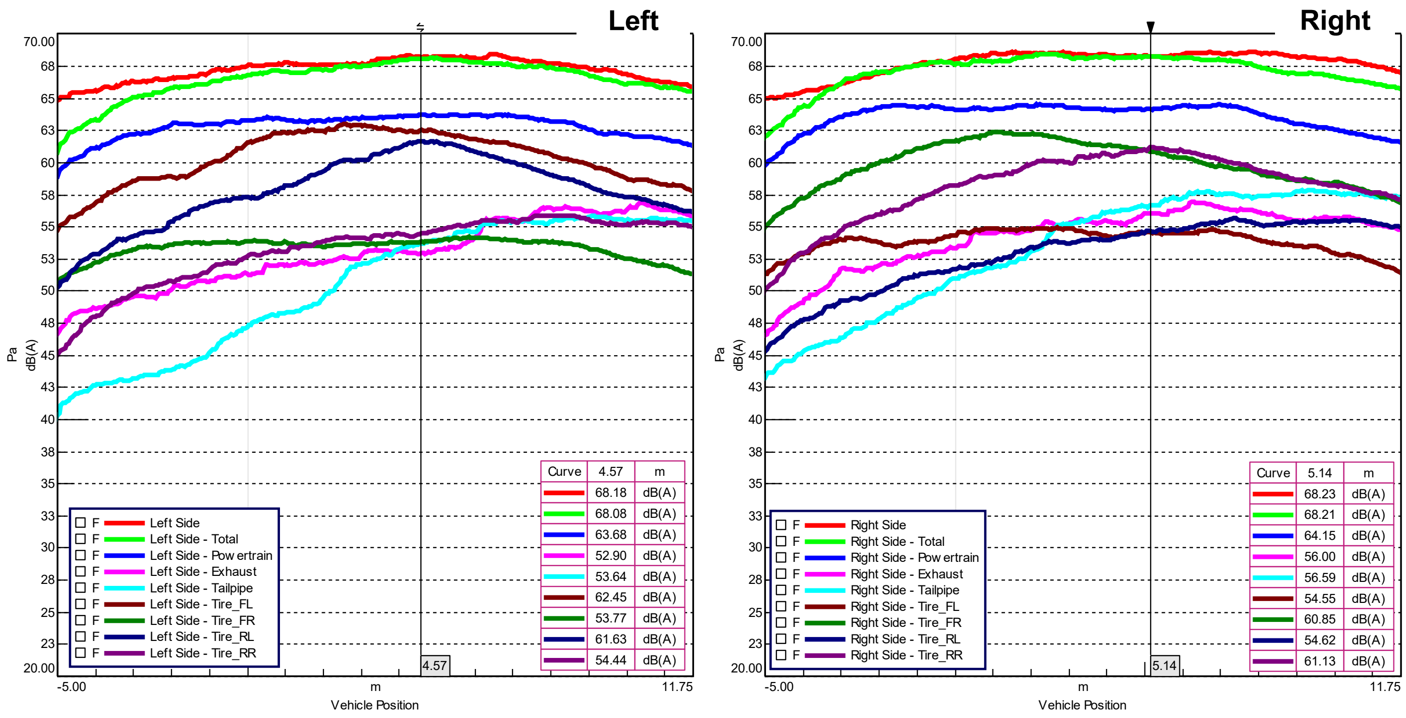
Good match between measured I-PBN result and synthesized ASQ I-PBN result



Demo

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

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1. What is TPA ?
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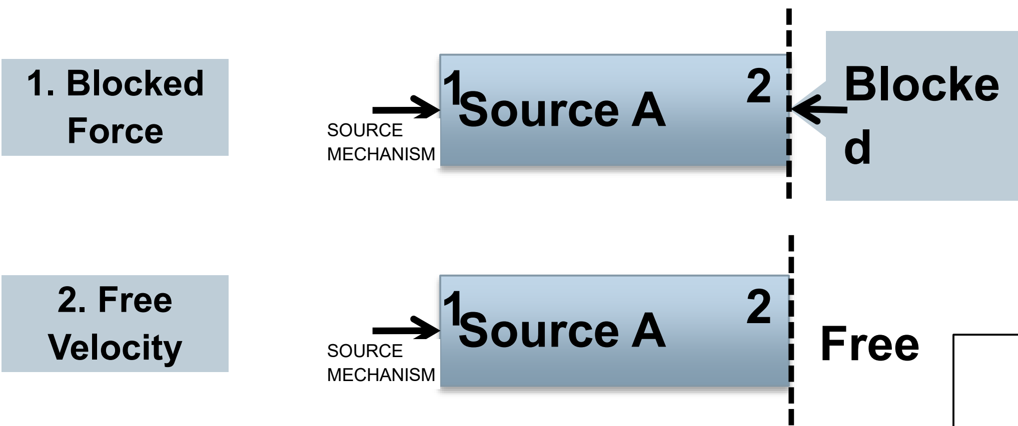
3. Strain TPA
4. Time TPA
5. Component TPA

Blocked force/free velocity principle



$\{F_{2Bl}\}$

$\{A_{2Free}\}$

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

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

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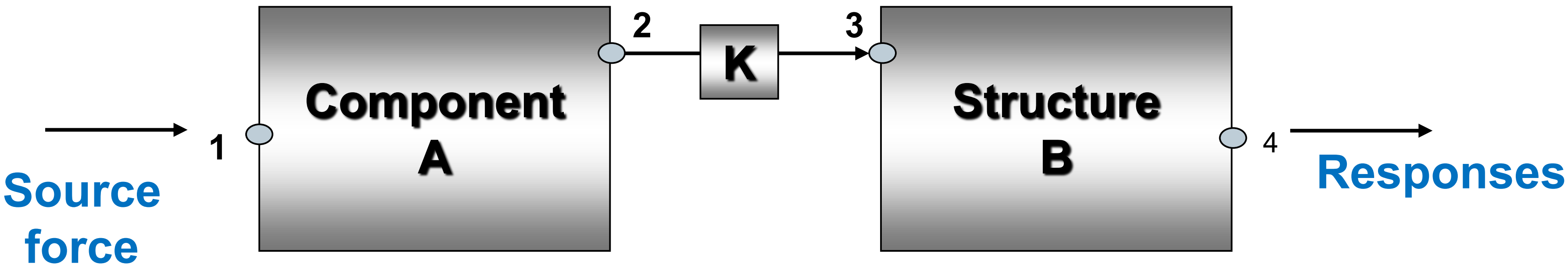
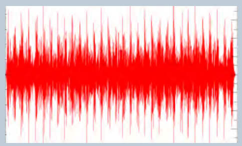


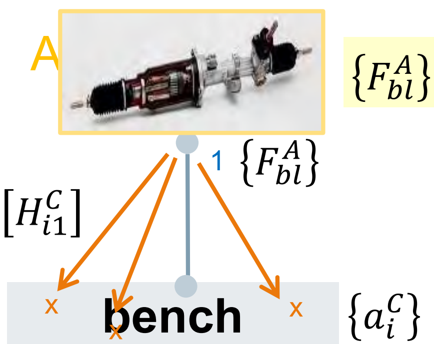
$$\{F_{2r}\} = \{F_{3r}\} = [H_{22}^{A} + H_{33}^{B} + K^{-1}]^{-1} * [H_{22}^{A}] * \{F_{2bl}^{A}\}$$

$$\{F_{2r}\} = \{F_{3r}\} = [H_{22}^{A} + H_{33}^{B} + K^{-1}]^{-1} * \{v_{2free}^{A}\}$$

Example Applications
Steering System

Source Mechanism	Invariant Source Synth. Model	Sub-Receiver	Receiver
 Steering System	 Blocked Forces & Impedances Mount Pos.	 Subframe FEM/TEST FRF	 Body FEM/TEST FRF

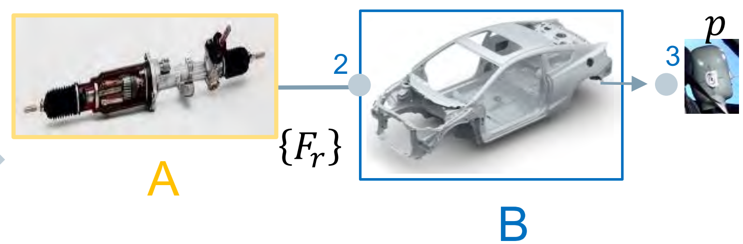
Invariant Source Load (TEST)



$$\{F_{bl}^{A}\} = [H_{i1}^{C}]^{-1} * \{a_i^C\}$$

$\{F_{bl}^{A}\}$

Full System Transfer Function



$$\{F_r\} = [H_{11}^{A} + H_{22}^{B} + K^{-1}]^{-1} * [H_{11}^{A}] * \{F_{bl}^{A}\}$$

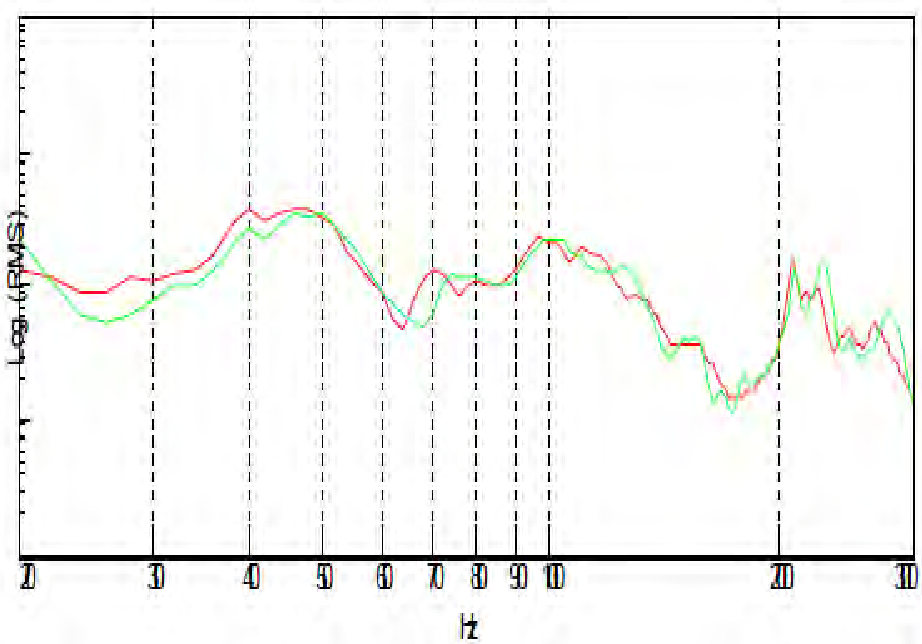
$$p = [H_{32}^{B}] * \{F_r\}$$

Example Applications
Road Noise - Tire

Source Mechanism

Tire
Road
Noise

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

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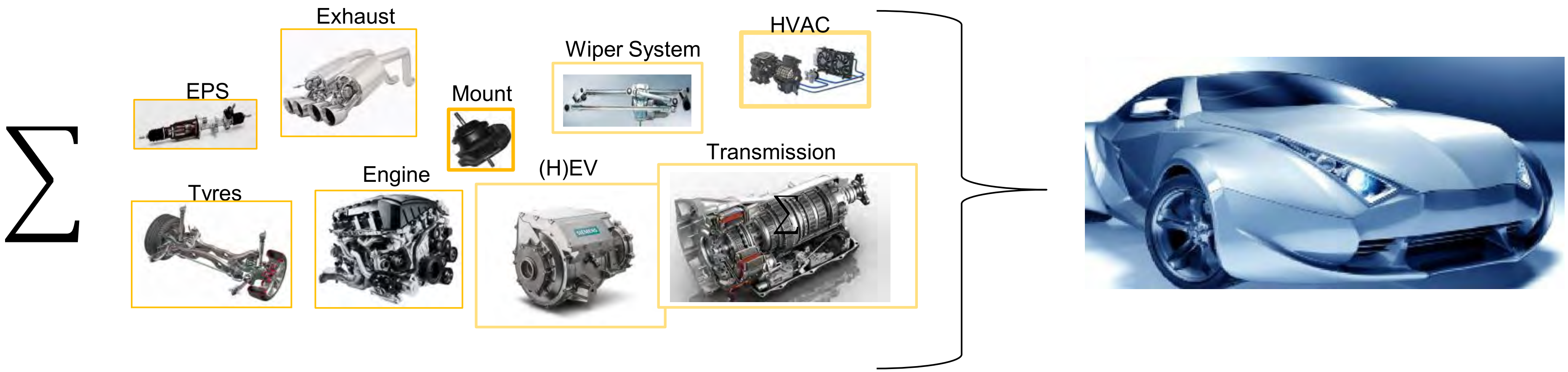

Benefits:

- 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

Filip Deblauwe
Technical Manager Test Solutions
CoE

Interleuvenlaan 68
3001 Leuven
Belgium

Phone: +32 16 384 437

E-mail:
filip.deblauwe@siemens.com

siemens.com