

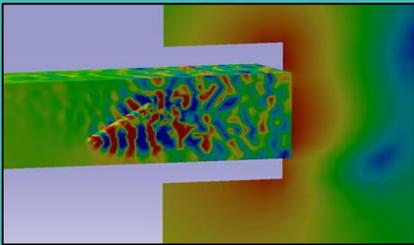
Fahrzeugkomfort und Akustik durch Weiterentwicklungen der Transferpfadanalyse optimieren

Arnd Balger

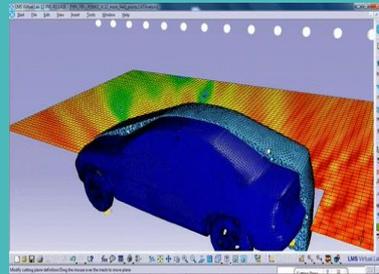
Typical NVH engineering challenges that can be addressed with Transfer Path Analysis

SIEMENS
Ingenuity for Life

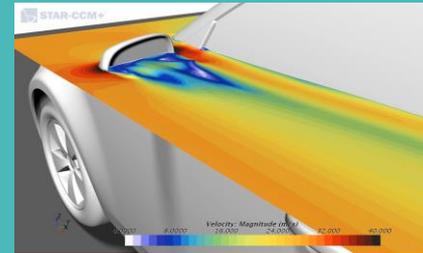
HVAC



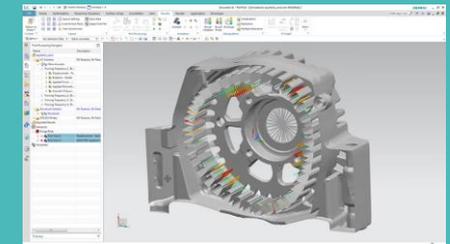
Pass-by noise



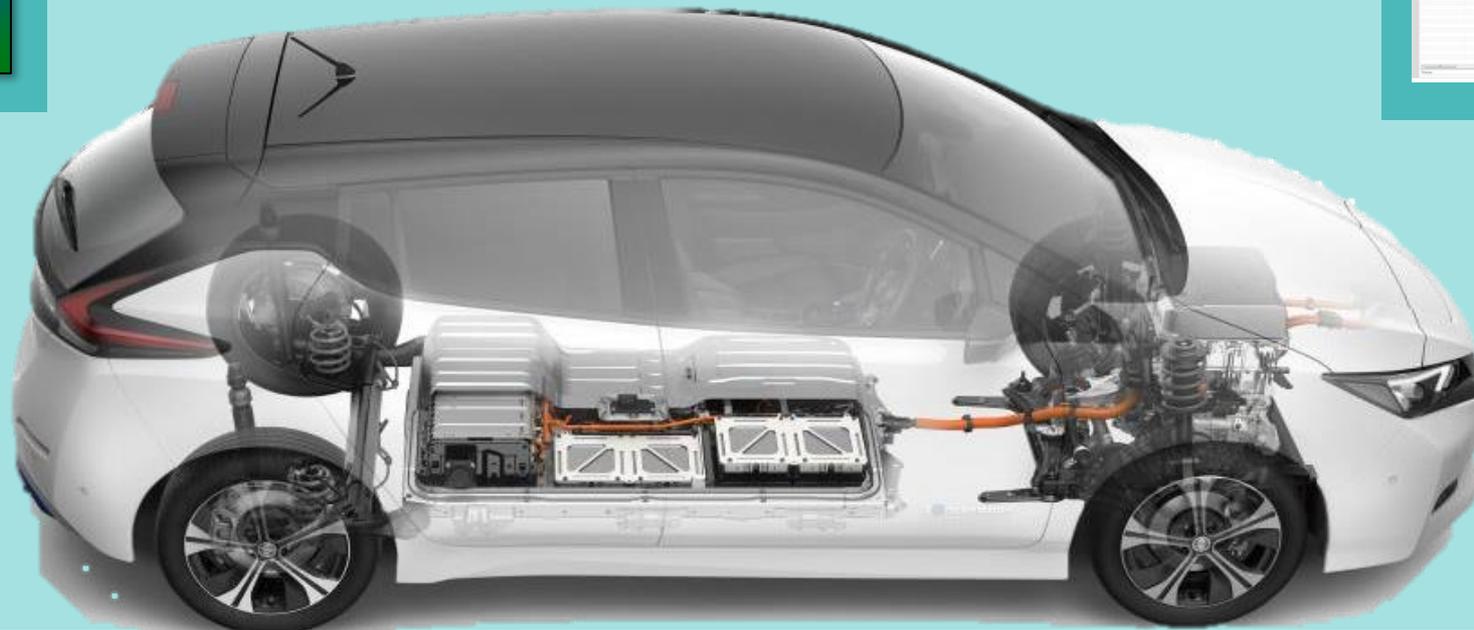
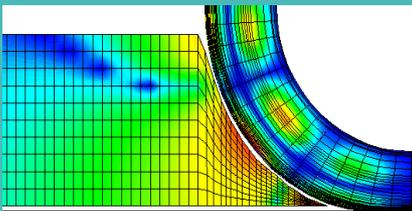
Wind noise



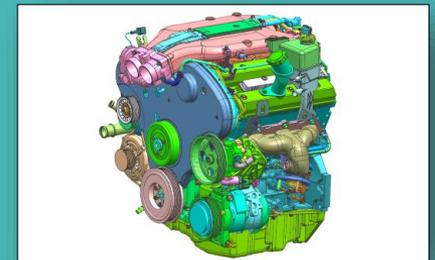
Electric motor



Road Noise



Engine



Fahrzeugkomfort und Akustik durch Weiterentwicklungen der Transferpfadanalyse optimieren

Einführung

Klassische Methoden der TPA

TPA im Zeitbereich

Komponenten-TPA

Modellbasierte TPA

Zusammenfassung + Ausblick



Transfer Path Analysis

Source-transfer-receiver approach

Transmission



Drive line



HVAC



Exhaust



Wiper System



EPS



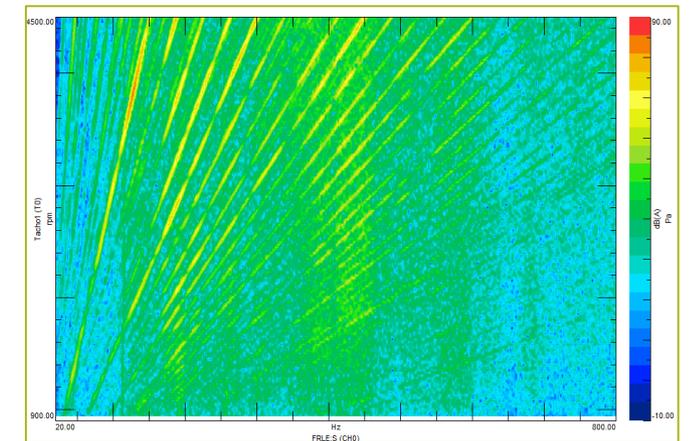
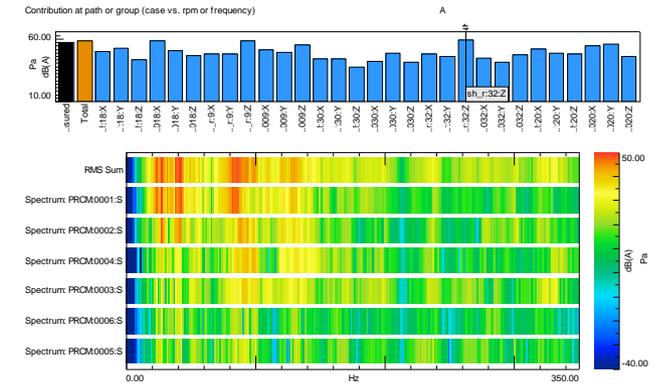
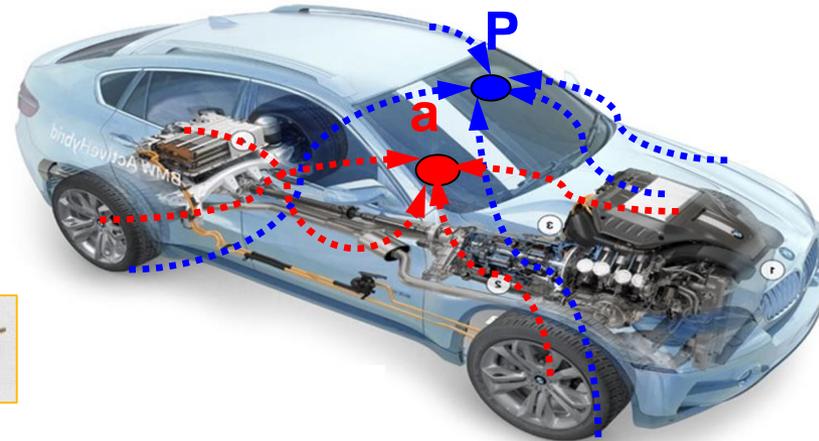
(H)EV



Tyres



Engine



Source (F_i, Q_j)

X

Transfer (NTF)

=

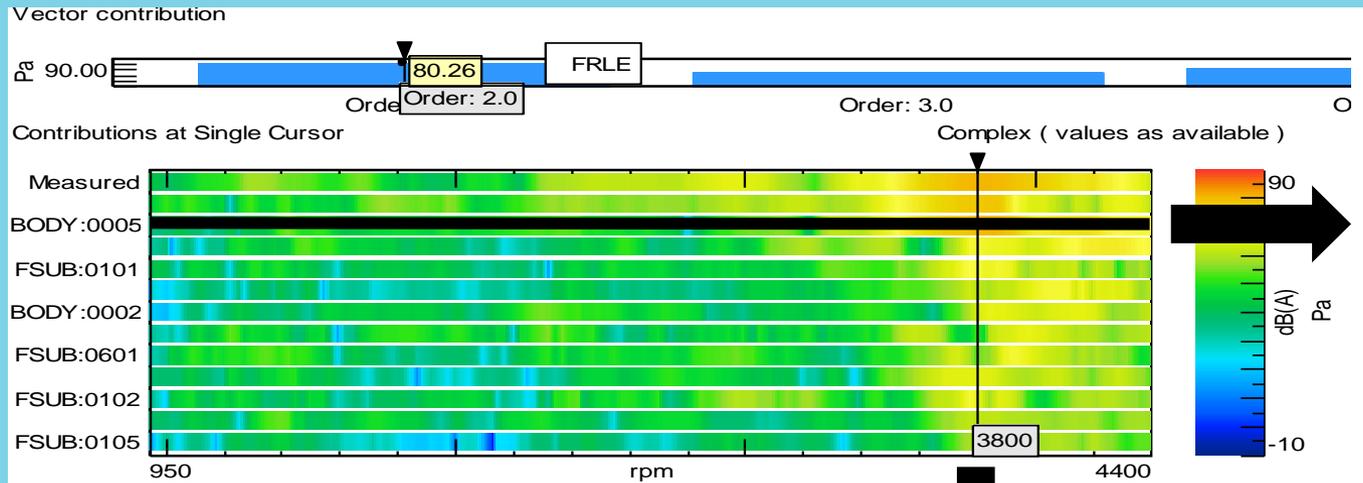
Receiver (y_k)

Introduction to Transfer Path Analysis

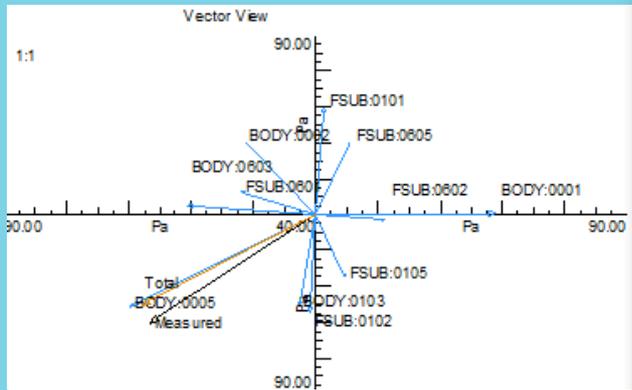
TPA as part of Contribution Analysis

Step 1: Contribution Analysis

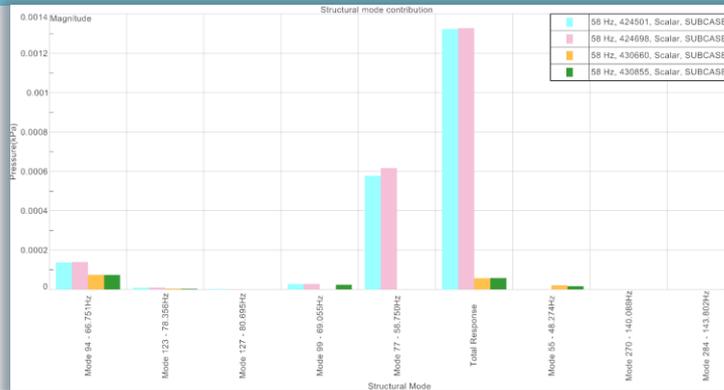
Paths



Frequency



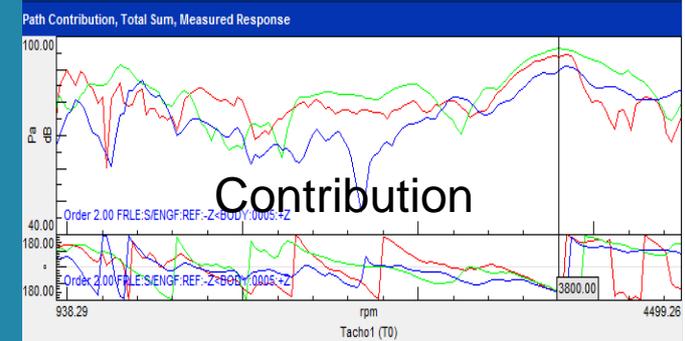
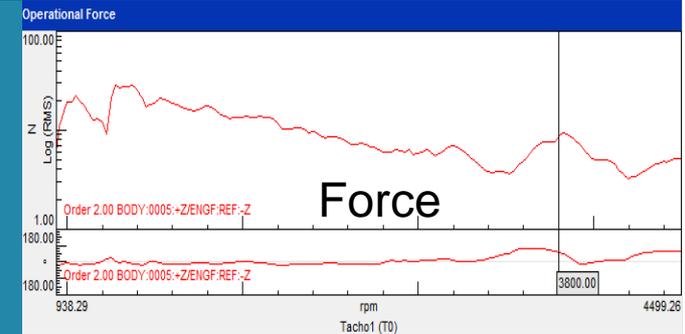
Amplitude Phase



Modal

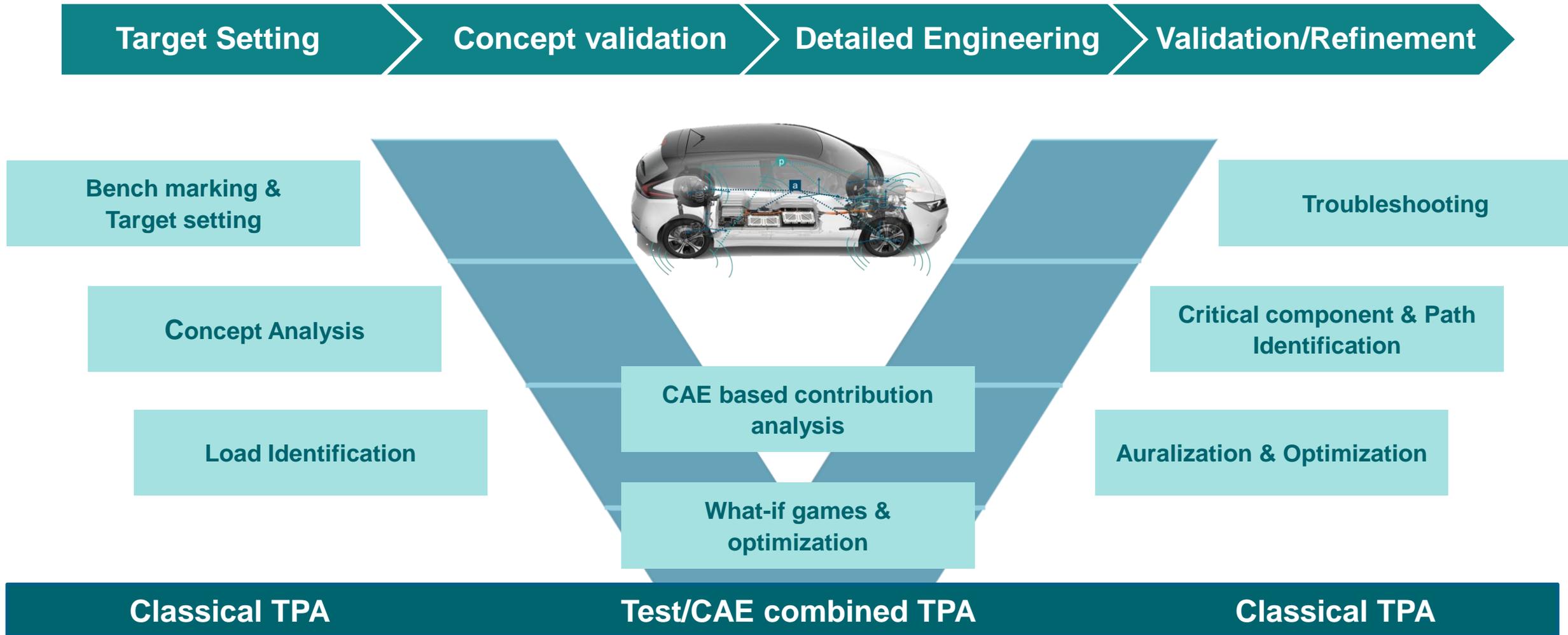
Step 2:

Path Source Transfer



Transfer Path Analysis

Throughout the vehicle development cycle



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Drive line



HVAC



Exhaust



Wiper System



EPS



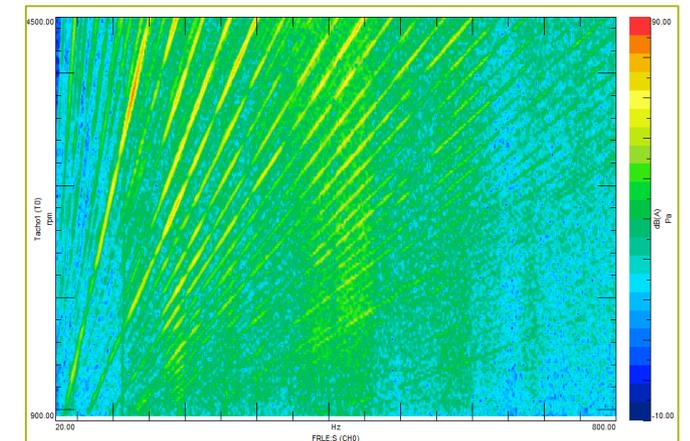
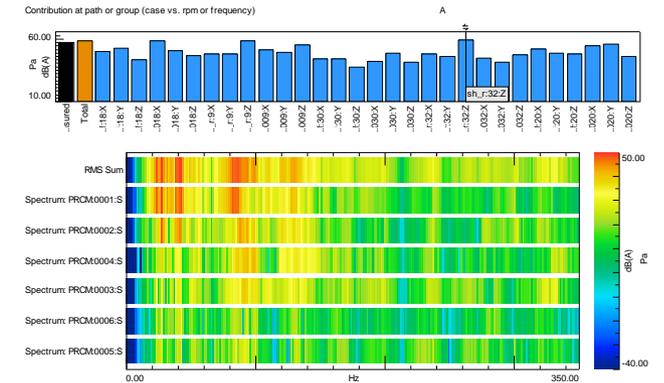
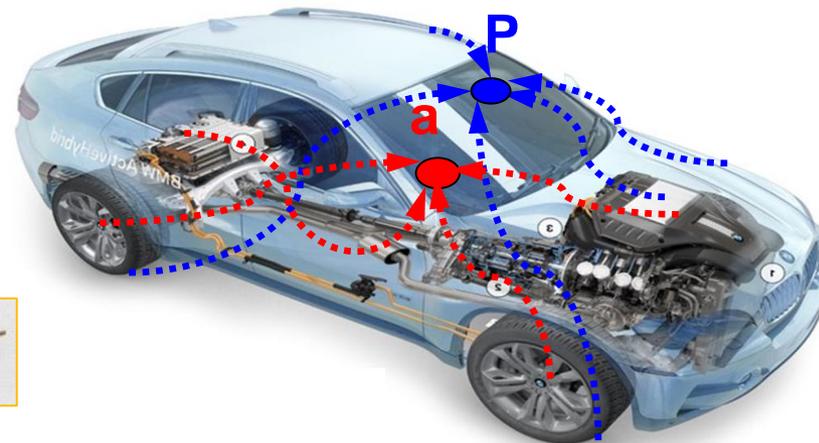
(H)EV



Tyres



Engine



Source (F_i, Q_j)

X

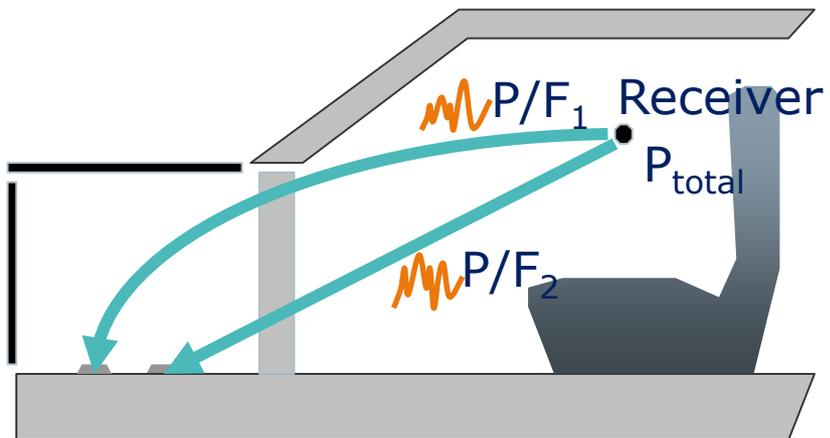
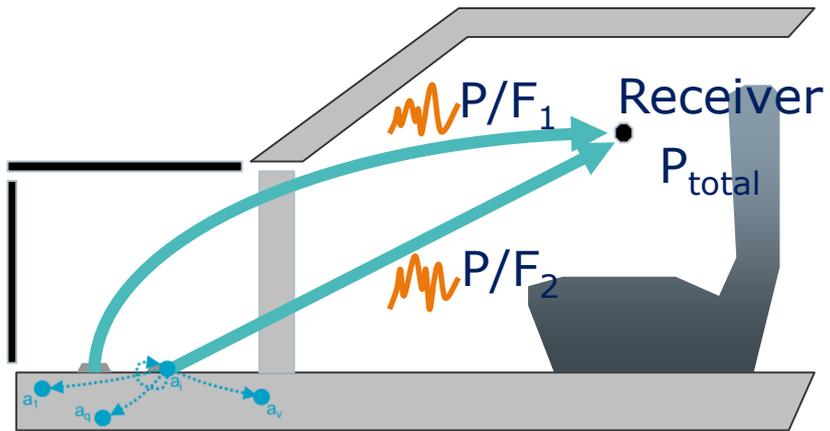
Transfer (NTF)

=

Receiver (y_k)

Traditional TPA methods

Efficient & Accurate FRF Acquisition



Direct FRF Measurements

- Modal Hammer
 - ✓ Common, limited quality and repeatability
- Shaker
 - ✓ shakers overcome hammer issues, if small and applicable



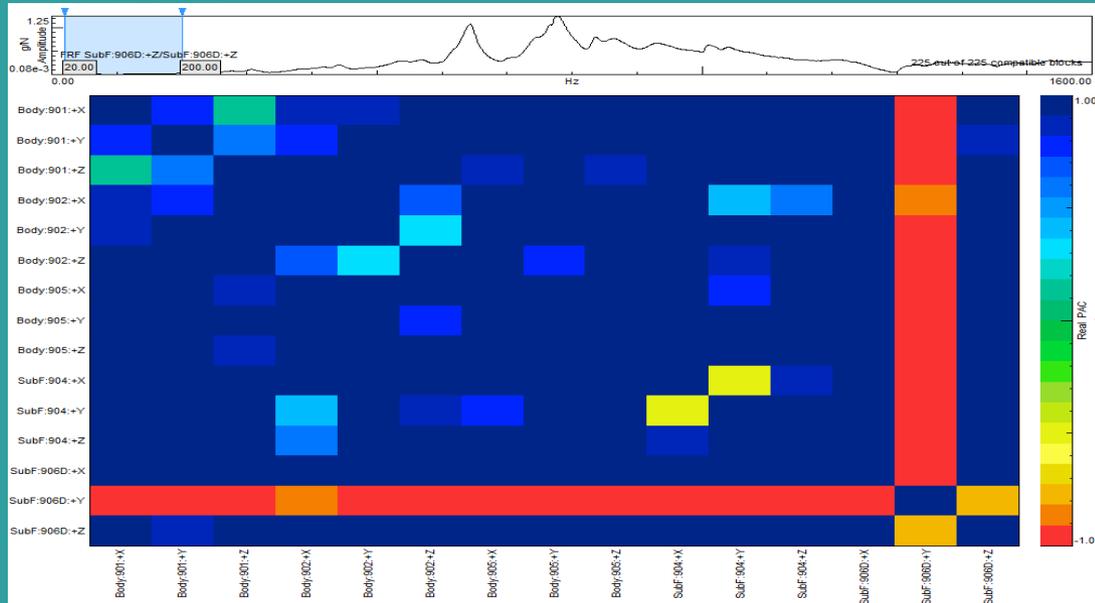
Reciprocal FRF measurement

- Measurement of multiple/all NTF (noise transfer functions) at once, faster than roving hammer or shakers

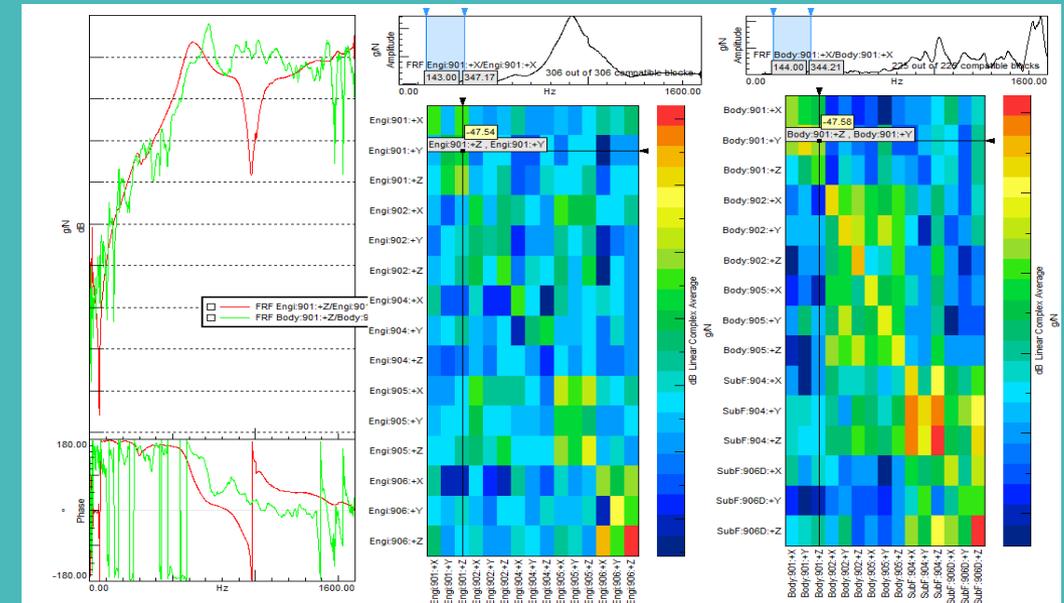


Traditional TPA methods

Requirements: Verify data quality and gain insight – the Heatmap



Instant verification of FRF consistency by checking reciprocity, linearity and directions errors



Gain insight in the system dynamics
1000+ FRFs in one view

Transfer Path Analysis

Source-transfer-receiver approach

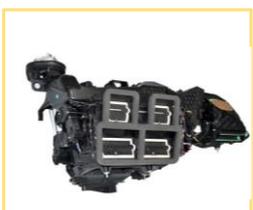
Transmission



Drive line



HVAC



Exhaust



Wiper System



EPS



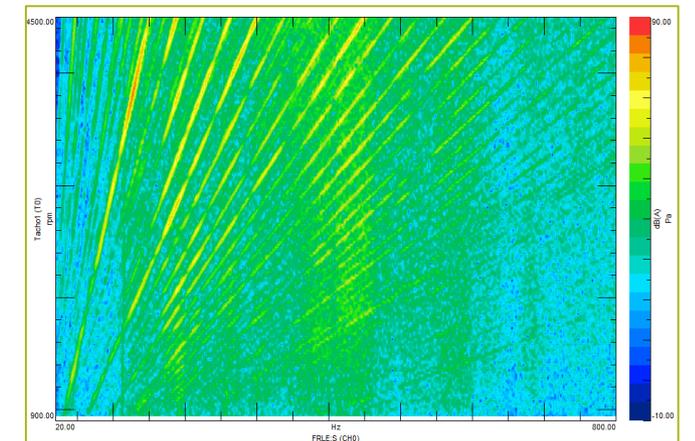
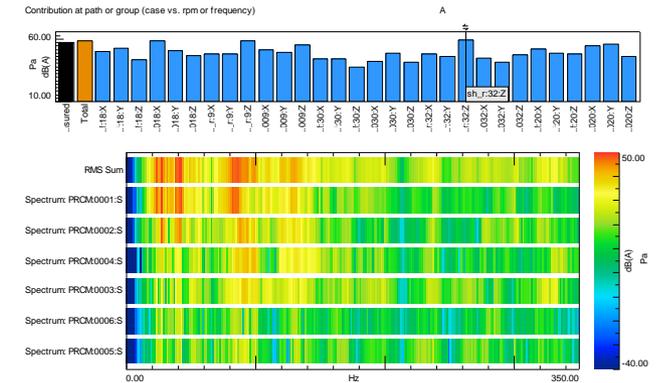
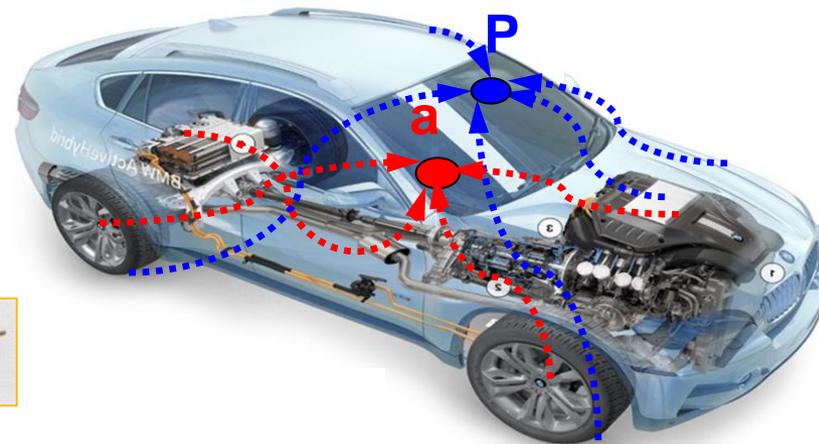
(H)EV



Tyres



Engine



Source (F_i, Q_j)

X

Transfer (NTF)

=

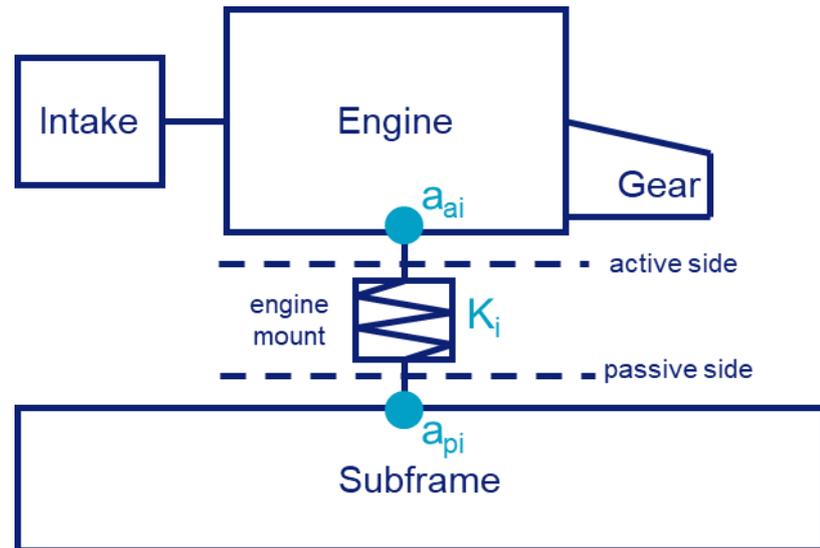
Receiver (y_k)

Load identification methods

Mount stiffness and Matrix inversion

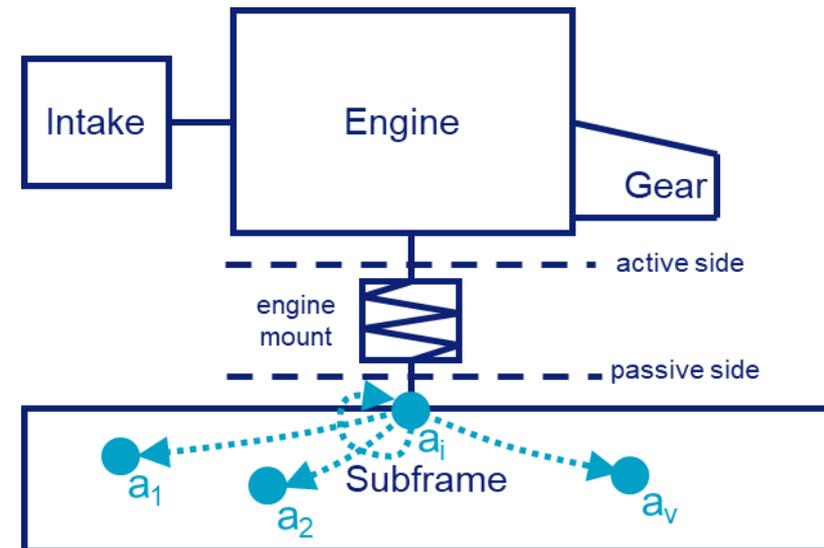
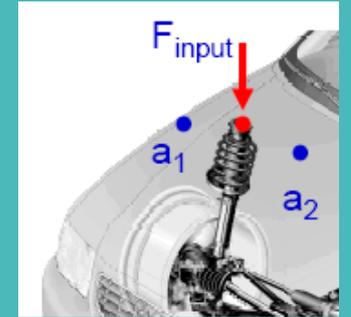
Mount Stiffness

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



Matrix Inversion

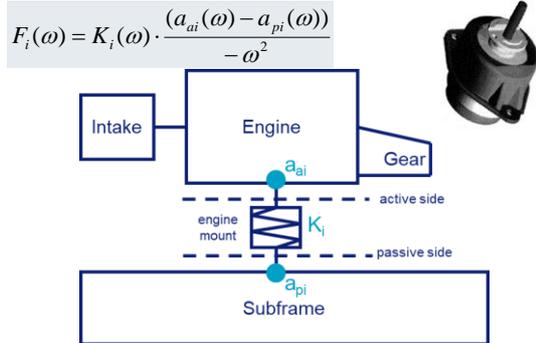
$$\{F(\omega)\} = [H(\omega)]^{-1} \cdot \{a(\omega)\}$$



Solution for load identification

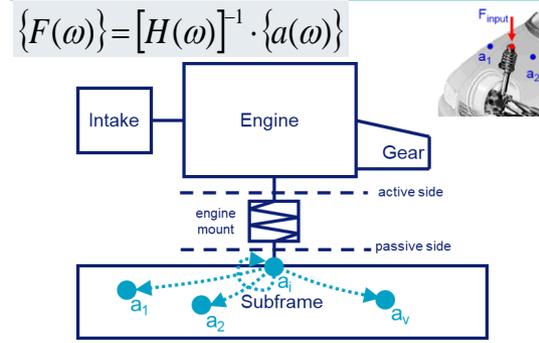
Traditional methods

Mount Stiffness



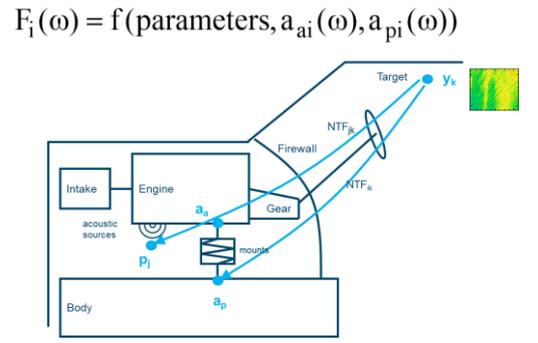
Fast and easy setup
Requires mount stiffness curves

Matrix Inversion



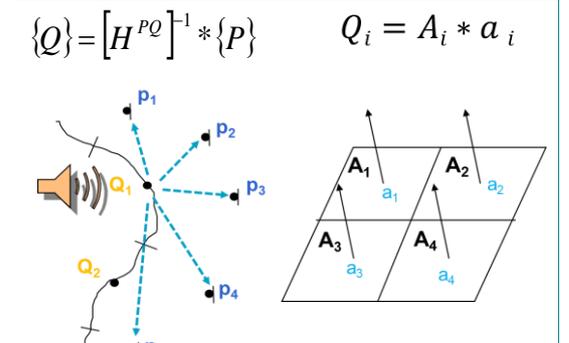
Works for all kind of connections (soft & rigid)
No stiffness curves required

OPAX



Reduced number of required measurements
Fast troubleshooting method

ASQ/Panel Contribution

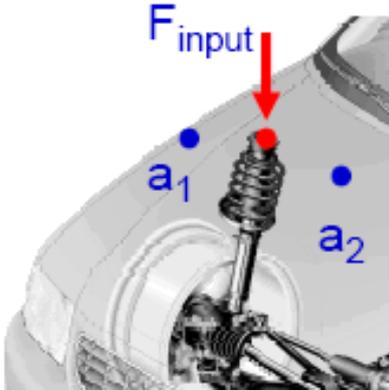


Quantify airborne contributions of nozzles, panels or component housings

Load identification techniques for fast troubleshooting to detailed structural & airborne load determination

TPA method: Strain sensors based

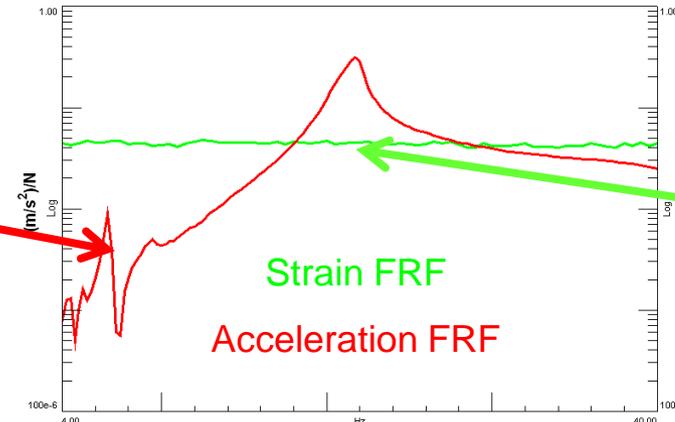
Separating nearby paths



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

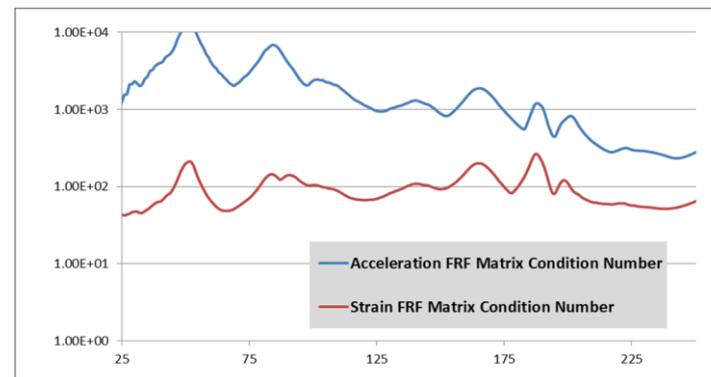
Classic approach: Acceleration Indicators

- Acceleration responses are dominated by a **limited** amount of **global** structural body modes
- Potential limitation for force estimation possibilities



Advanced approach: Strain Indicators

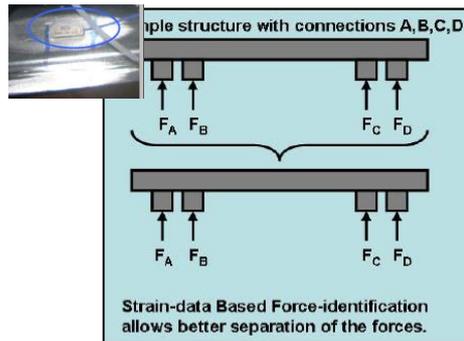
- Strain responses are dominated by a **high** amount of **local** structural body modes
- Extended possibilities for load separation / identification



Solution for load identification

Advanced methods

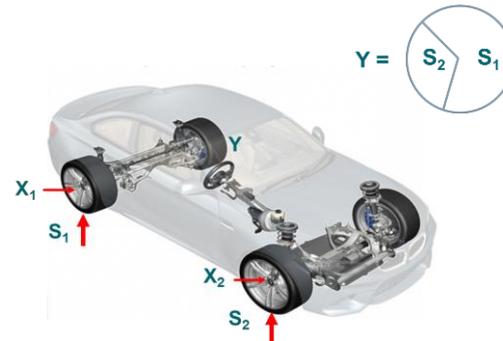
Strain-based



Separate strongly coupled forces

Low Frequency Analysis

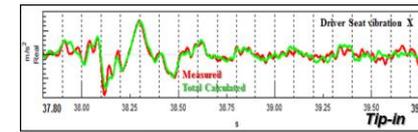
Multi-reference



Multi-source noise & vibration issues

Road noise analysis

Time domain



Analyze transient phenomena

Listen to partial contributions

Tackle issues from every possible angle – from simple systems to complex structures

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Modellbasierte TPA

Zusammenfassung + Ausblick



Frequency-domain vs. Time-domain TPA

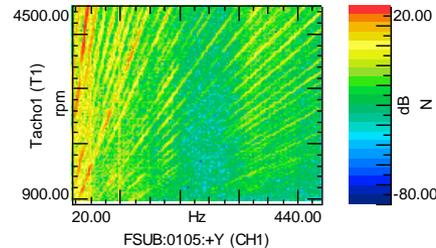
Frequency-domain TPA

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

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 ...

Loads (orders, spectra)

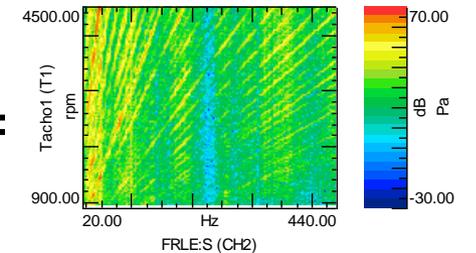


X

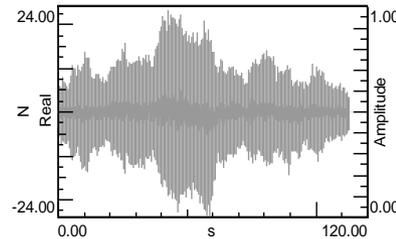
NTF

Frequency transfer model

Path contributions (orders, spectra)

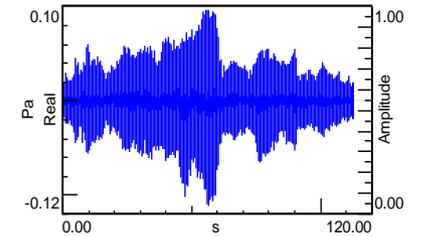


=



⊗

FIR Filter



=

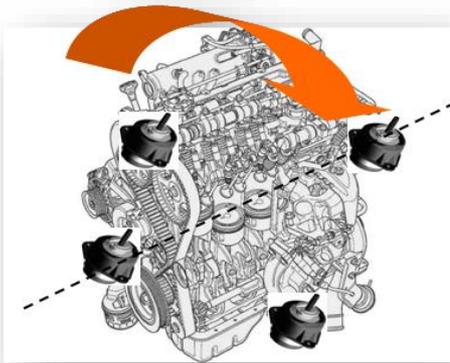
Loads (time traces)

Path contributions (time traces)

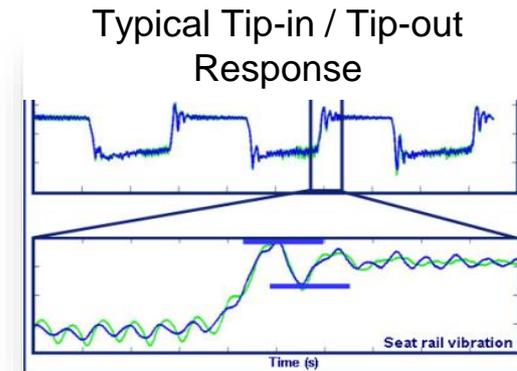
Auralization, Signature Analysis, Sound Quality metrics ...

Time-domain TPA for Tip-in/Tip-out

Application Example



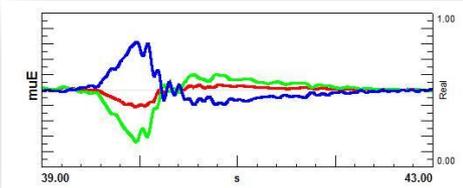
Transient torque oscillations in the driveline
Amplified by P/T, suspension and body modes
Resulting seat and steering-wheel vibrations



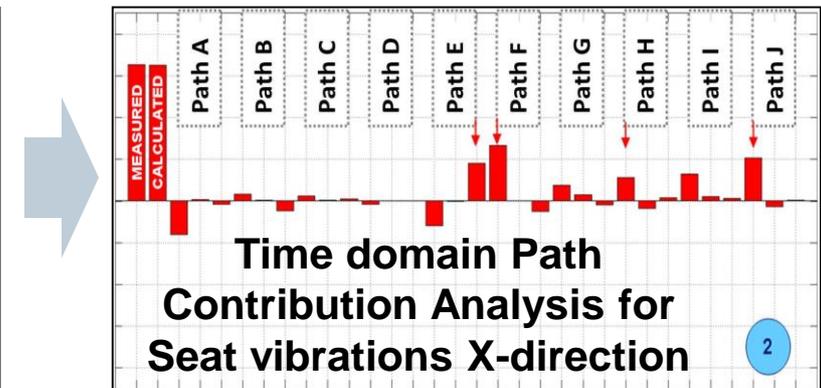
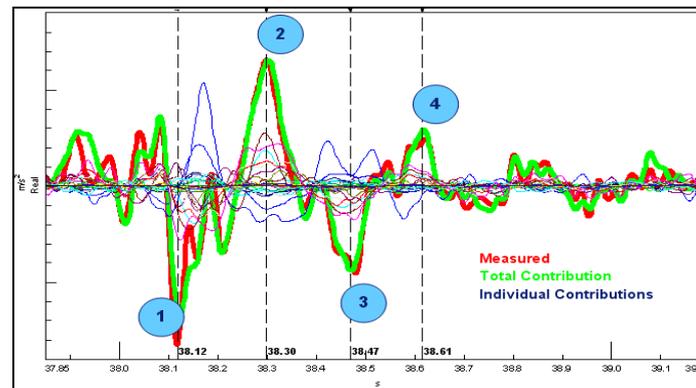
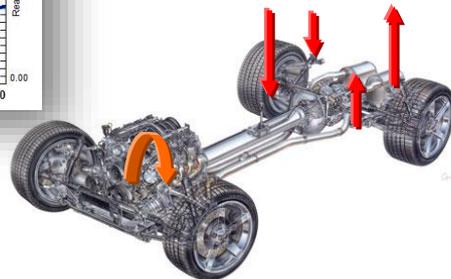
Transient Load identification
Strain gage technology
Low frequency

...in "full NVH Context"
To link transient loads
to Dynamic Interface Forces...

...Transfer Path Analysis (TPA)
Insights in contribution
to NVH Comfort

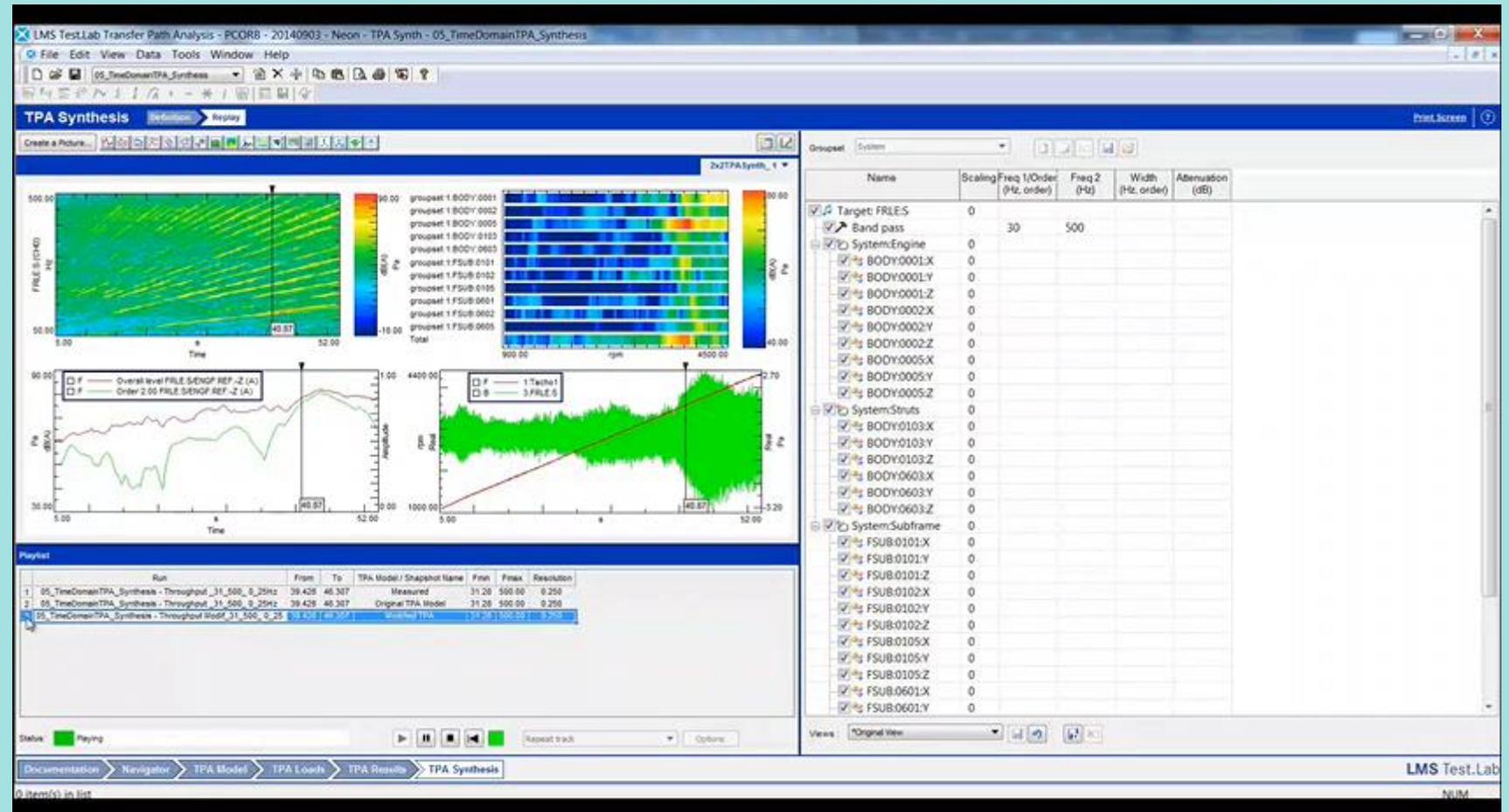
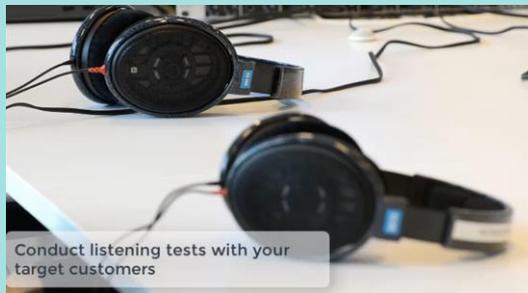


Strain responses
(right) during Tip-in



Transfer Path Analysis: More insight with TPA Synthesis

Immediate assessment of design modifications. real-time filtering and auralization of partial contributions for subjective sound qualification and A/B comparisons



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TPA im Zeitbereich

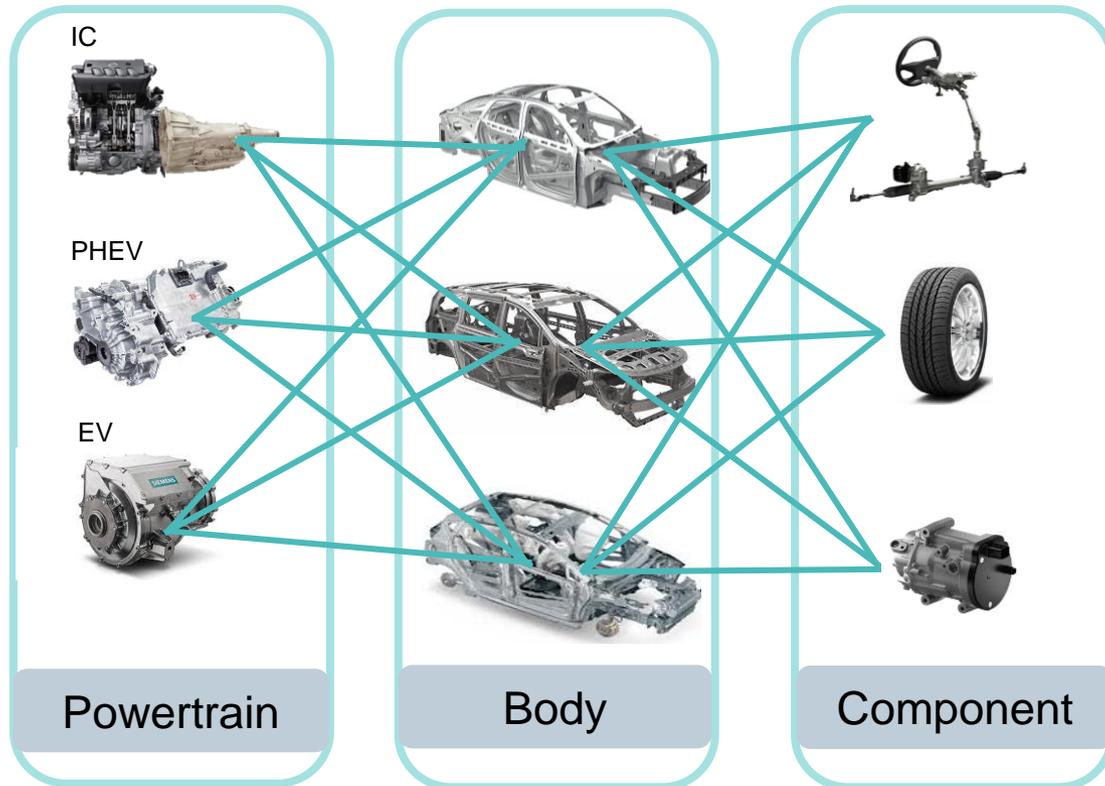
Komponenten-TPA

Modellbasierte TPA

Zusammenfassung + Ausblick



Automotive OEMs have to reduce full vehicle testing to handle wide variety of vehicles

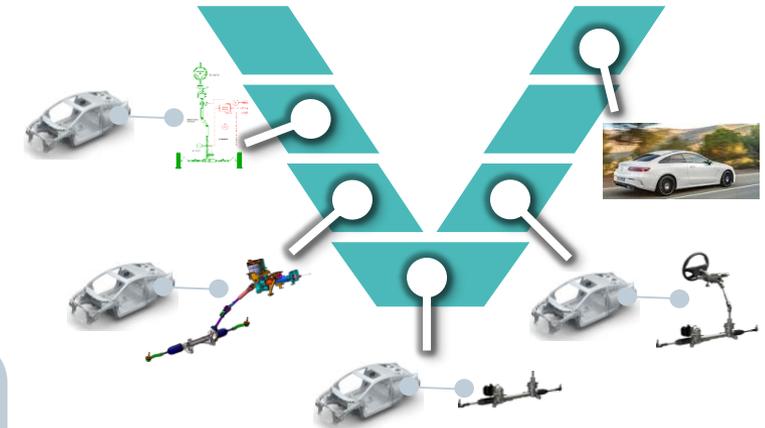


of vehicle variants



- Increasing testing effort
- Prototype availability?
- Impact of modification?
- ...

Frontloading



Front-loading vehicle
level component
NVH testing

How to ensure NVH performance while keeping development time and cost under control?

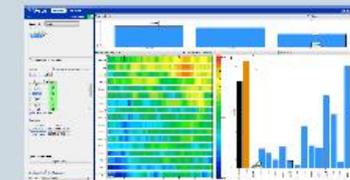
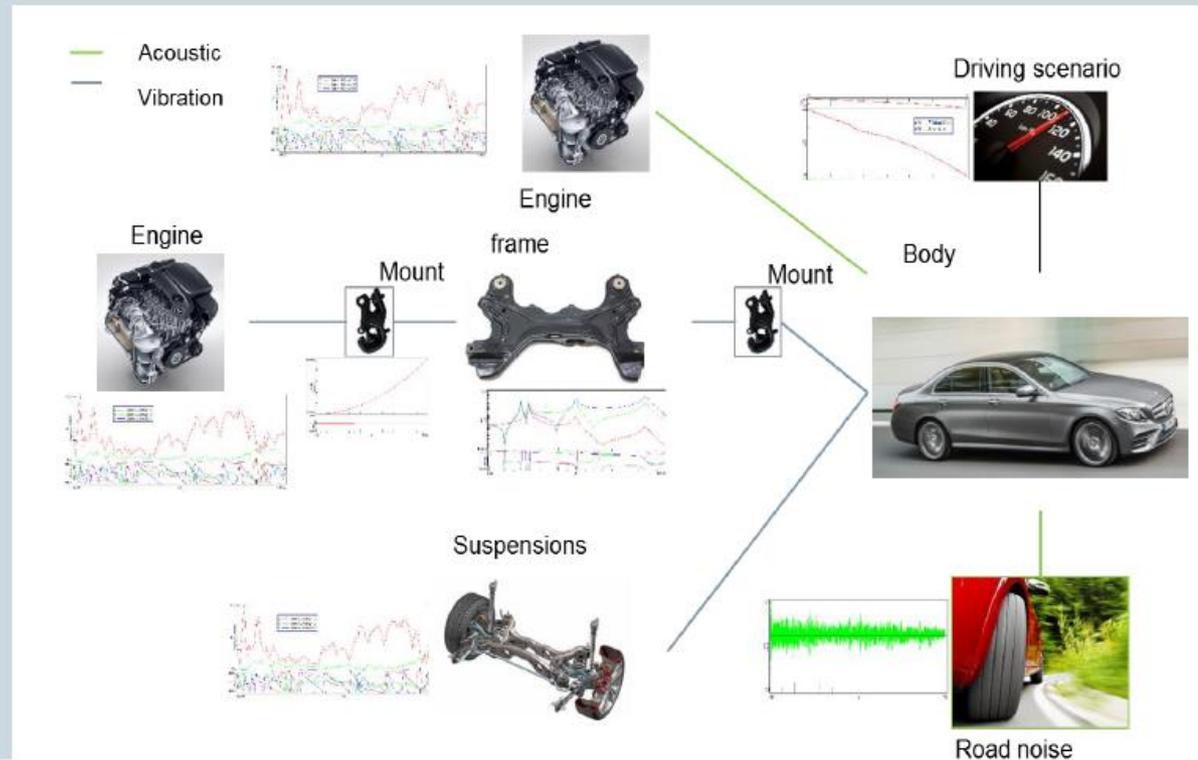
Component-based TPA for full vehicle NVH assessment

Enable NVH what-if analysis from concept to final troubleshooting

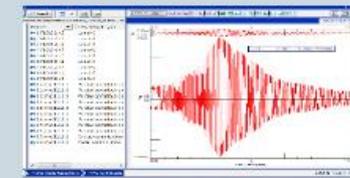
Characterize NVH contribution of sub-systems

Predict full-vehicle NVH using Test and Simulation models

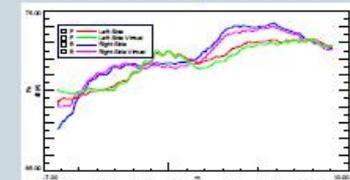
What-if-analysis by combining multiple sub-system variants



Contribution Analysis



Sound Synthesis

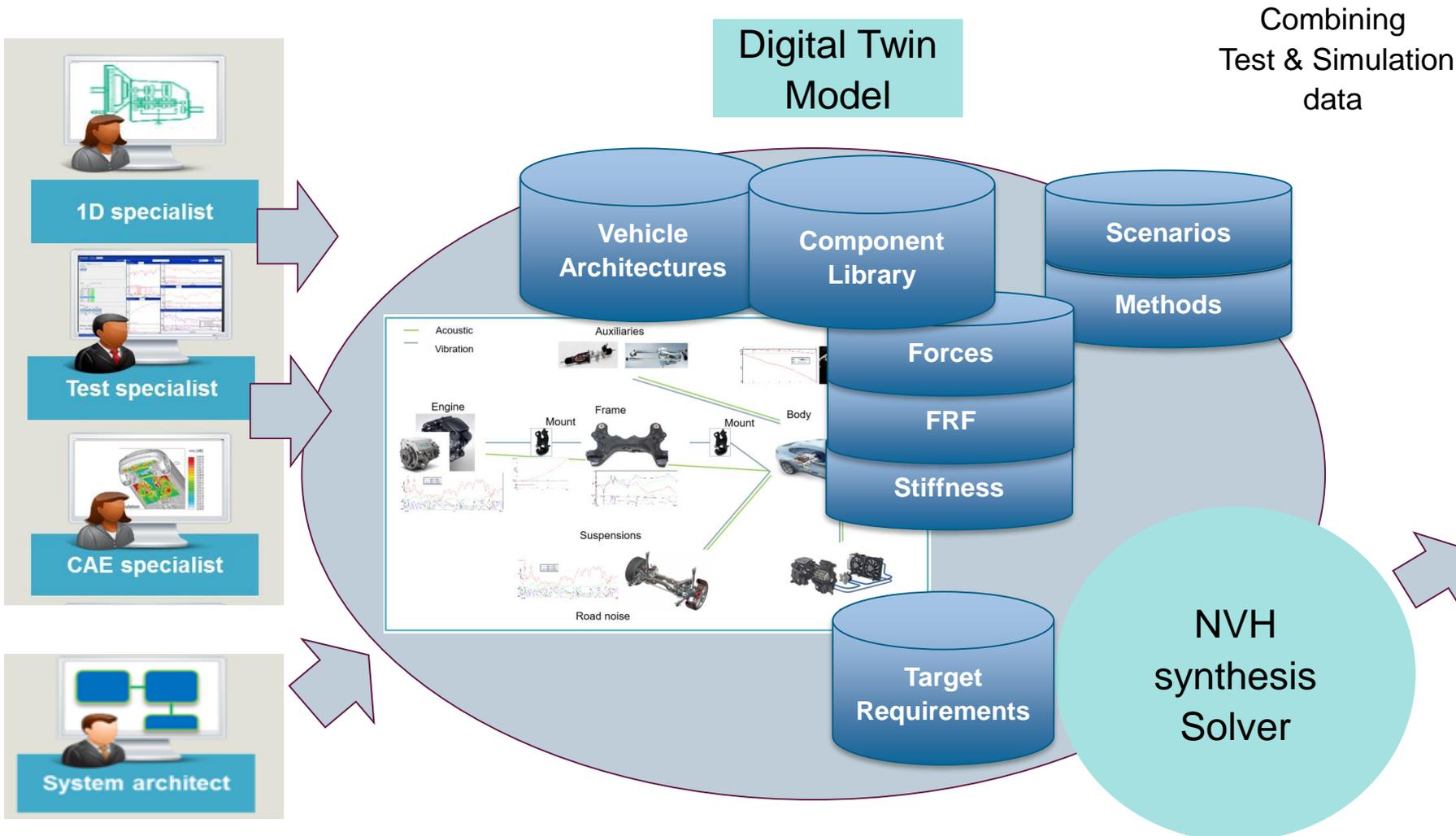


Pass-by Noise Synthesis



Component-based TPA for full vehicle NVH assessment

Testlab NVH Synthesis – Concept



Compare Contribution Analysis

Pass-by Noise Synthesis

Sound Synthesis Result

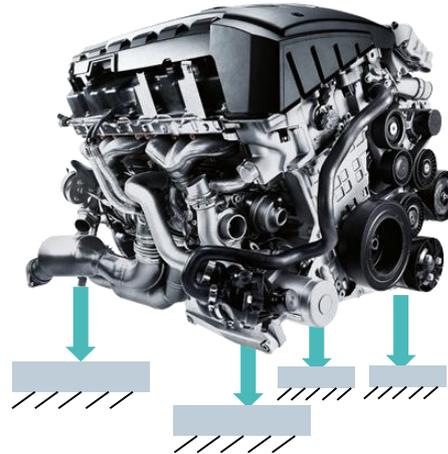
NVH Driving Simulator Evaluation

Component-based TPA

Invariant load characterization

Structure-borne:

Blocked Forces



Airborne:

Volume Velocities



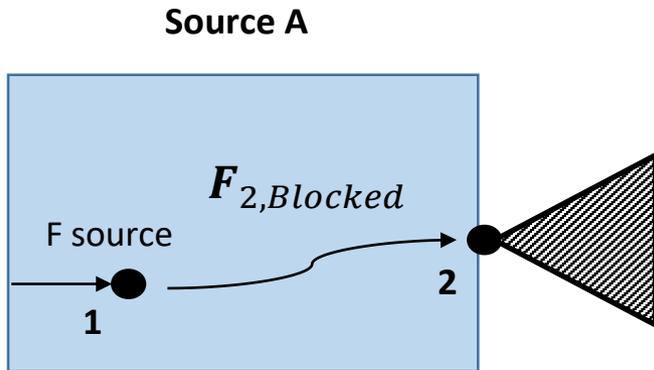
Invariant load characterization

Receiver independent, allowing:

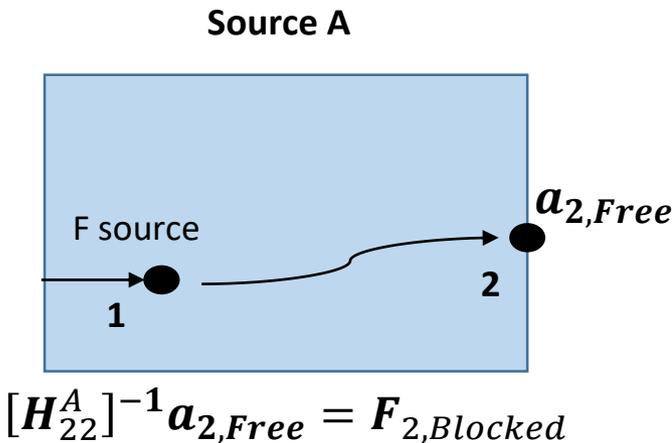
- Validating sources against receiver independent targets
- Benchmarking or validating modifications
- Predicting NVH performance in arbitrary source-receiver assemblies

Three possible methodologies to obtain independent source description

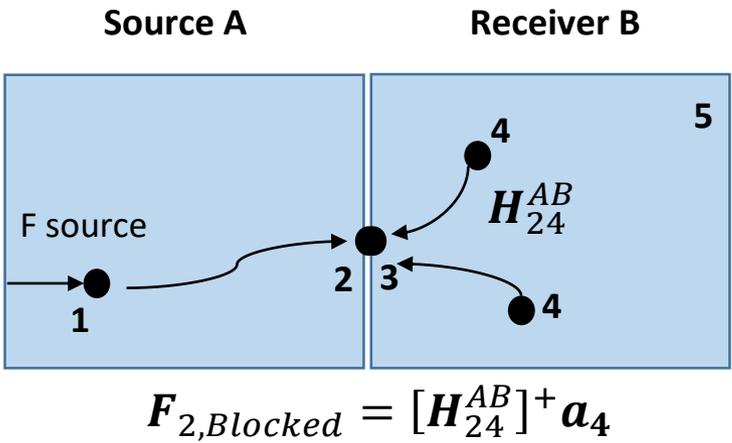
1. Blocked Force



2. Free Velocity/Acceleration



3. In-Situ TPA



Rigid test rig → Often not possible

Source in free free conditions (ISO 9611)

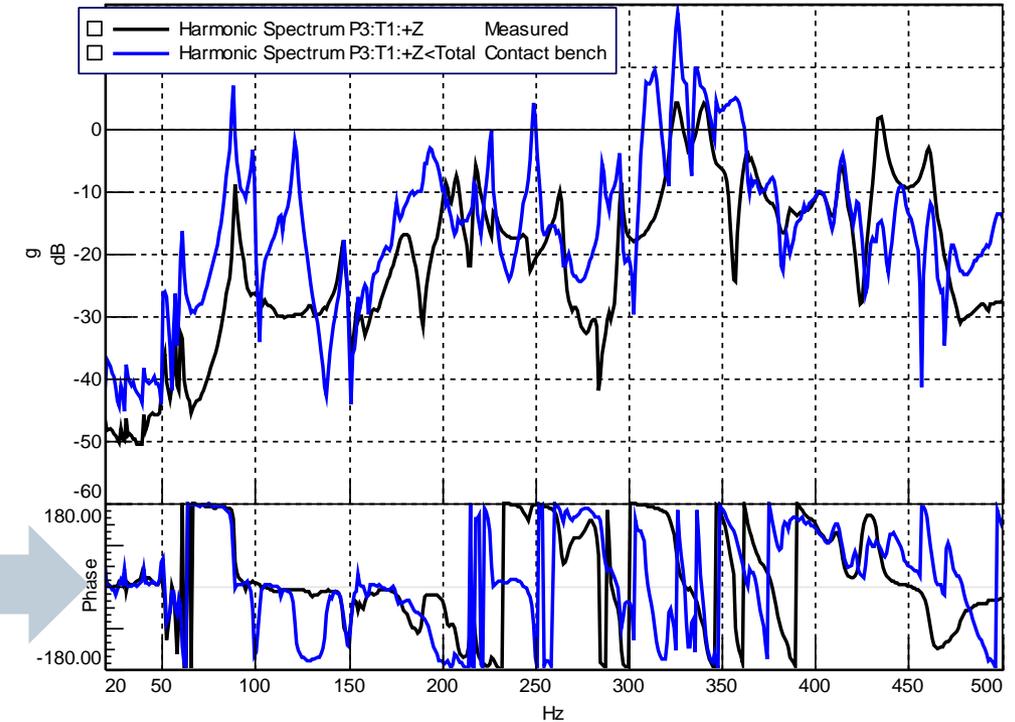
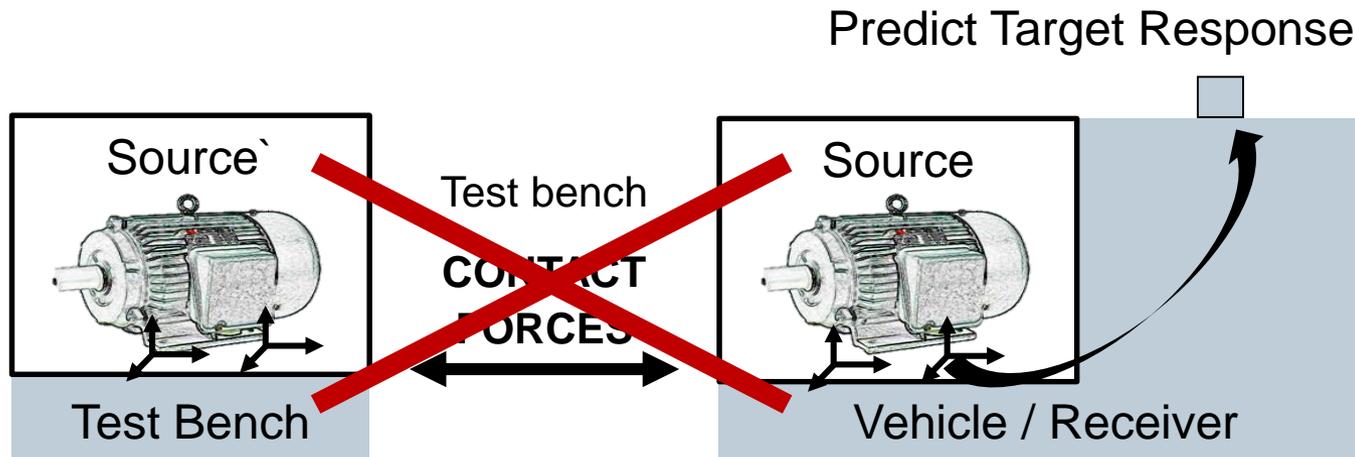
Any receiver is valid (ISO 20270-2019)

Source: Mondot, Petersson, Characterization of structure-borne sound sources: The source descriptor and the coupling function 1987

Source: Elliott, Moorhouse, Characterization of the structure borne sound sources from measurements in-situ, 2008

Example: Source-Receiver interaction

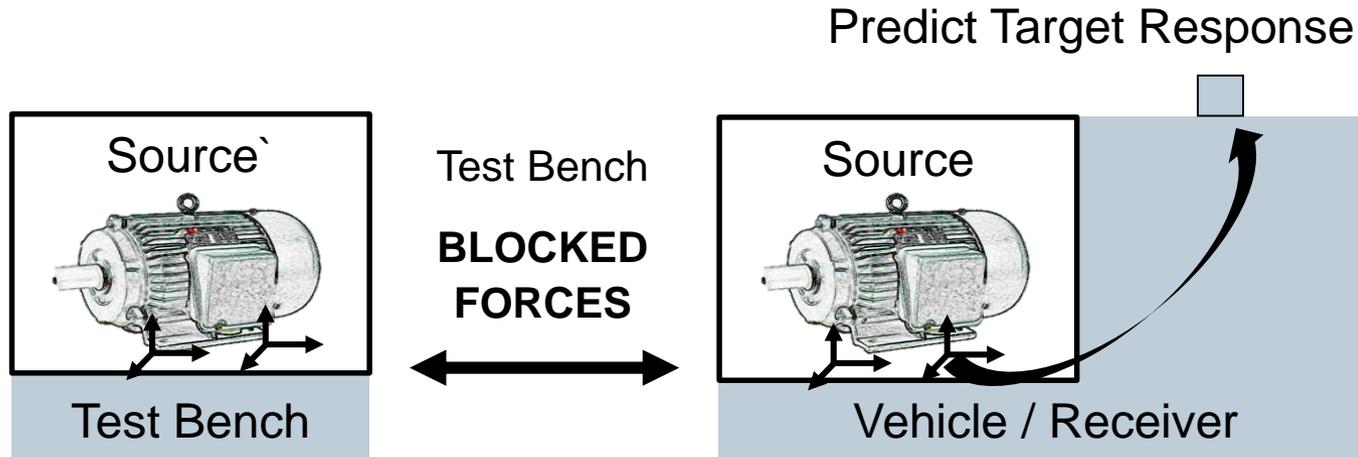
Strong coupling case – Structure Borne



Predicted target deviates from measured target!

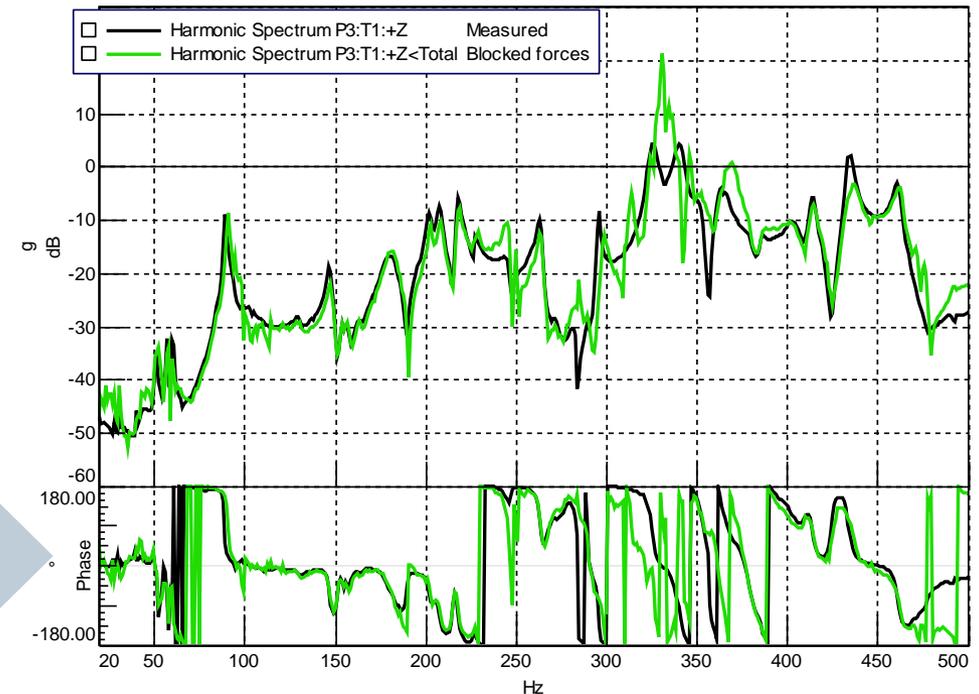
Example: Source-Receiver interaction

Strong coupling case – Structure Borne



- + Invariant Load Strength
- +- Conditioning similar to classical Matrix Inversion TPA
- - Combining with FBS puts high demands towards data quality

Predicted target matches measured target!



Virtual Point Transformation

Accurate FRFs at interface connection points

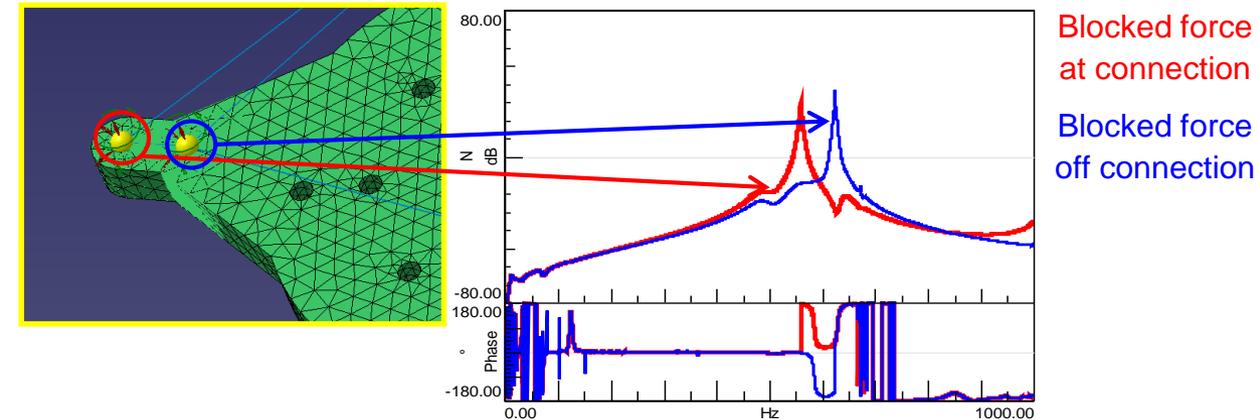
Challenge:

- High quality transfer functions at precise locations.
- Transfer functions at difficult to access positions
- Translational and rotational transfer functions (DOFs)

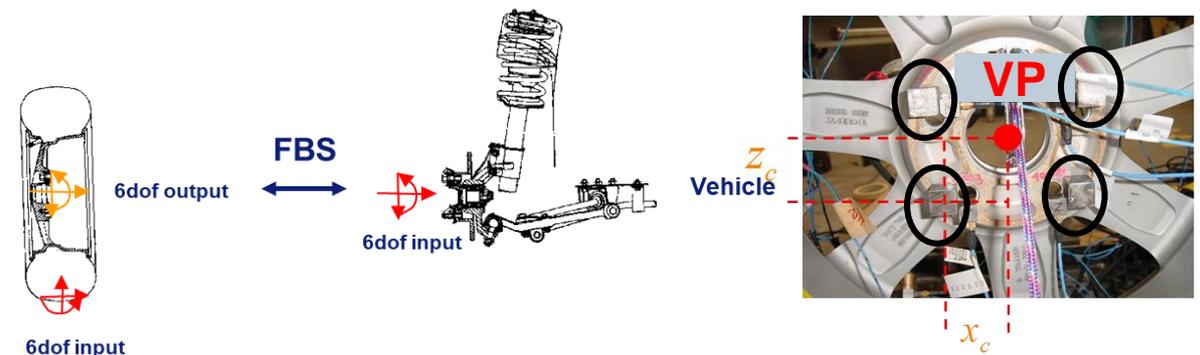
Solution:

- Geometrical Reduction / Virtual Point Transformation
- Assumption: local rigidity in the connection
- Input: Geometry Information and FRFs

VP for correct blocked force estimation

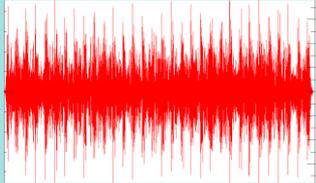


VP for correct assembly using FBS



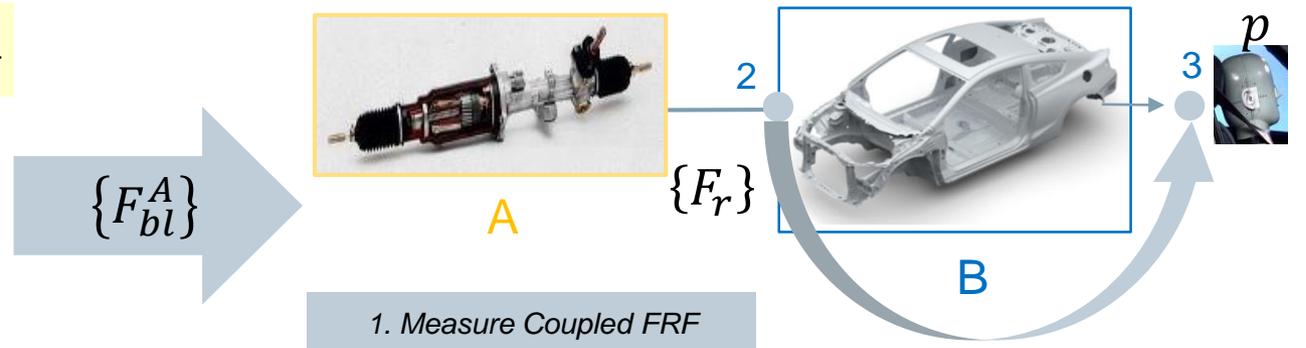
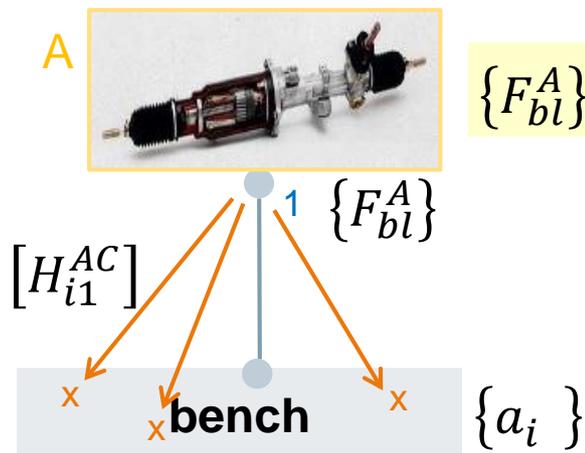
Component-based TPA

Application example of a steering system

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

Invariant Source Load (TEST)

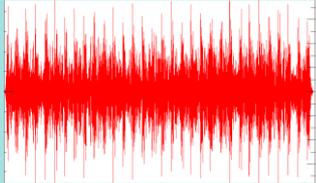
Full System Transfer Function



$$p = [H_{32}^{AB}] * \{F_{bl}^A\}$$

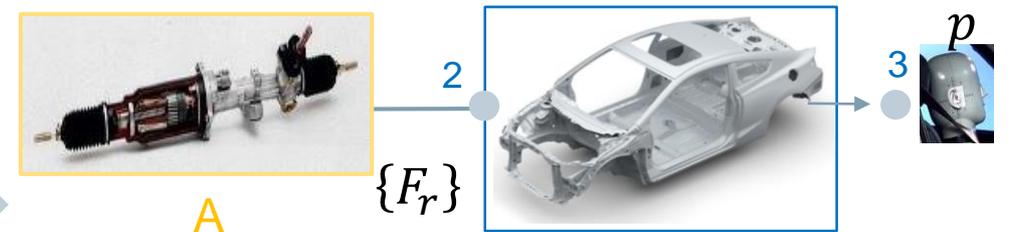
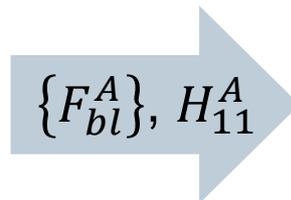
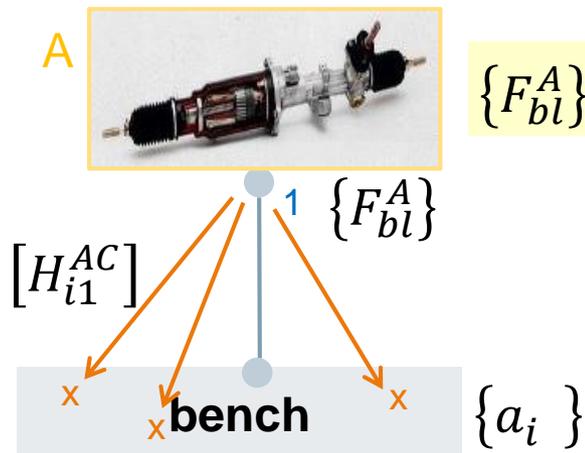
Component-based TPA

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Invariant Source Load (TEST)

Full System Transfer Function



2. Calculate Coupled FRF

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

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

Component-based TPA Assembly & Prediction (Simcenter Testlab 2019.1)

1. Assembly Definition

Targets

Paths

Source Paths

Point ID	Quantity	Unit
1 t1:Z	Acceleration	g
2 t2:Z	Acceleration	g

Point ID	Load quantity	Load unit	Response quantity	Response unit
1 supAconn:1X:X	Force	N	Acceleration	g
2 supAconn:1Y:Y	Force	N	Acceleration	g
3 supAconn:1Z:Z	Force	N	Acceleration	g
4 supAconn:2X:X	Force	N	Acceleration	g
5 supAconn:2Y:Y	Force	N	Acceleration	g
6 supAconn:2Z:Z	Force	N	Acceleration	g

Point ID	Load quantity	Load unit	Response quantity	Response unit
1 eng1:1X:X	Force	N	Acceleration	g
2 eng1:1Y:Y	Force	N	Acceleration	g
3 eng1:1Z:Z	Force	N	Acceleration	g
4 eng1:2X:X	Force	N	Acceleration	g
5 eng1:2Y:Y	Force	N	Acceleration	g
6 eng1:2Z:Z	Force	N	Acceleration	g

2. Load & Contribution Prediction

Amplitude

Path	Unit	Method	Functions	Matrix Inv. Threshold
1 supAconn:1X:X	N			
2 supAconn:1Y:Y	N			
3 supAconn:1Z:Z	N			
4 supAconn:2X:X	N			
5 supAconn:2Y:Y	N			
6 supAconn:2Z:Z	N			

Matrix Inversion

Calculate

Matrix Inversion Threshold

Criterion Type: Number

Number of omitted singular values: 0

Use path FRFs

Use source path FRFs

Use mount stiffness FRFs

Progress Indication

Processing data...

Amplitude Linear Complex Average

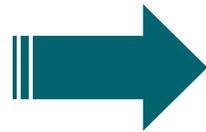
FBS calculation for coupling source and receiver

The complete Component Based TPA process fully integrated in Simcenter Testlab

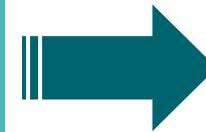
Airborne example application: PBN Performance Prediction

SOURCE

Invariant description of sources

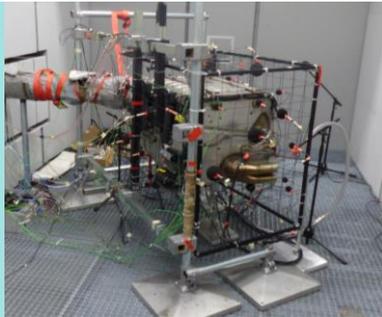


Recombine with selected components to synthesize SYSTEMS

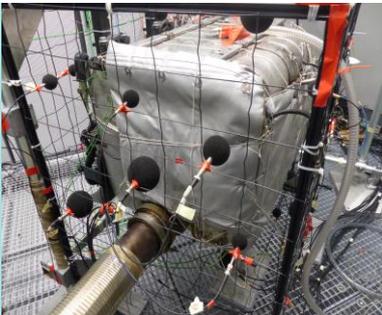


Predict NVH performance

VARIANT
A



VARIANT
B



All Design Variants

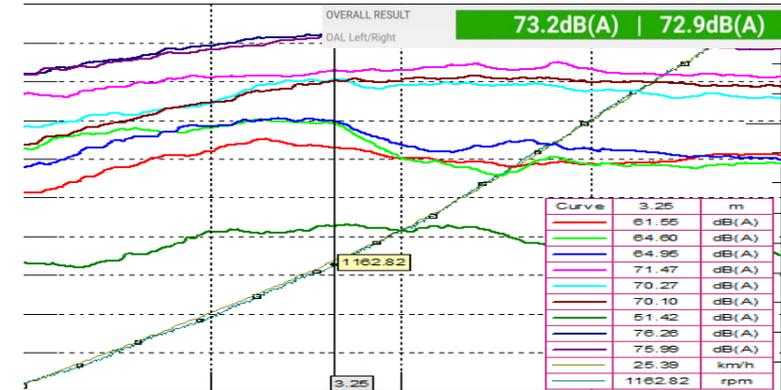
VEHICLE
1



VEHICLE
VARIANTS



Vehicle Variants



Simcenter Testlab NVH Synthesis Model Based Development for NVH



1. NVH Component Definition

The screenshot displays the VVA Publisher software interface. On the left, there are panels for 'Input Basket' and 'DOF M' (Input and Output). The main workspace shows a 'Save and Publish Component' dialog box with properties like 'Name: VISA2', 'Blocked Forces Enabled: False', and 'Minimum Frequency: 0 Hz'. Below this, there are two plots: a line graph showing 'Amplitude value (summed energy) [g]' vs 'Hz' and a heatmap showing the same metric across different DOF combinations.

2. NVH Synthesis Applications

The screenshot shows the 'Pass-by Noise Synthesis' application interface. It includes a 'Vehicle Body' dropdown set to 'PbnAcqBody', a table of parameters (Vehicle Body name, Number of Input DOF id's, Number of Array DOF id's, PBN Room Layout name, Vehicle overhang), and a 'Load as Octave Sections' section with 'IRPBN_LOAD_TIRES'. A 'Test Scenario' section is also visible. On the right, a sidebar contains four items: 'Compare Contribution Analysis' (with a bar chart), 'Pass-by Noise Synthesis' (with a line graph), 'Sound Synthesis Result' (with a waveform), and 'NVH Driving Simulator Evaluation' (with a simulator image).

Enable NVH what-if analysis from concept to final troubleshooting

Fahrzeugkomfort und Akustik durch Weiterentwicklungen der Transferpfadanalyse optimieren

Einführung

Klassische Methoden der TPA

TPA im Zeitbereich

Komponenten-TPA

Modellbasierte TPA

Zusammenfassung + Ausblick

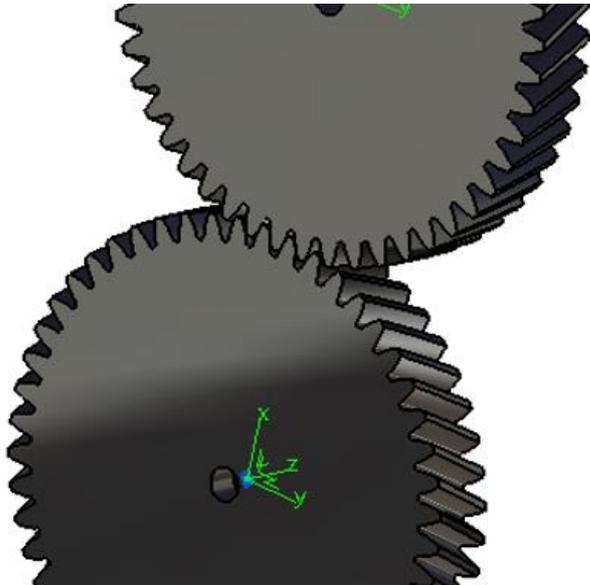


Model-base TPA

Gearbox Noise – Multi-Body Dynamics + Structural Dynamics

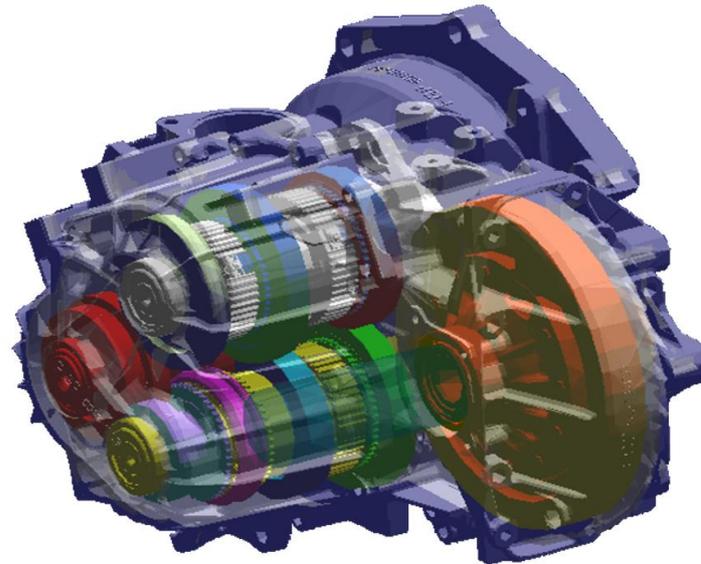
SOURCE

Gear rattle or meshing forces in function of volute profile, misalignment, torque load, ...



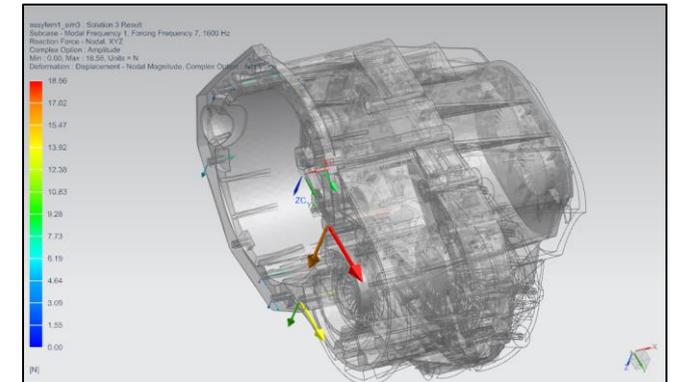
PATH TRANSFER

Full system of gears, axles and body including their respective flexibility

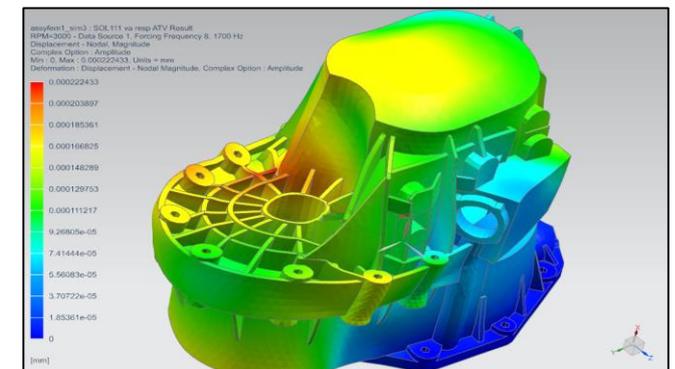


RECEIVER

Operational connection forces (to body)



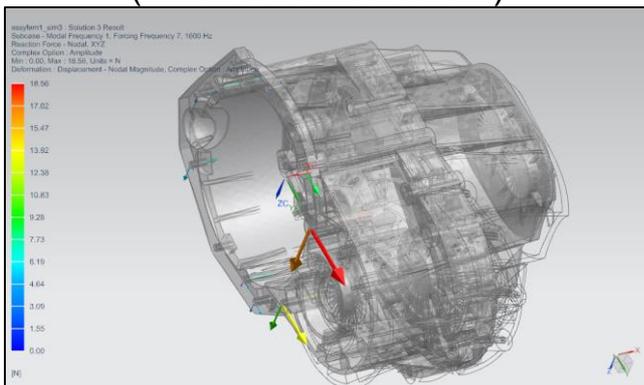
Operational surface vibrations



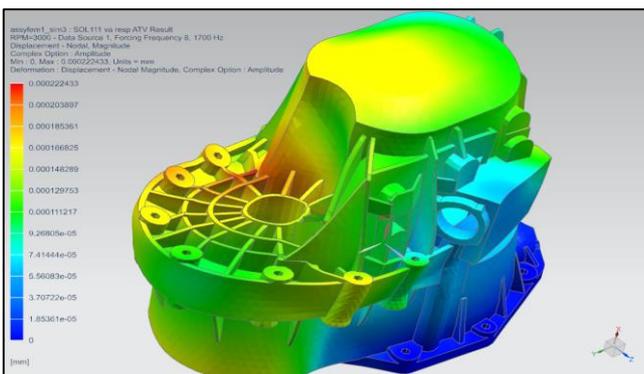
Gearbox Noise – Structural Dynamics and Acoustics

SOURCE

(structure borne noise)

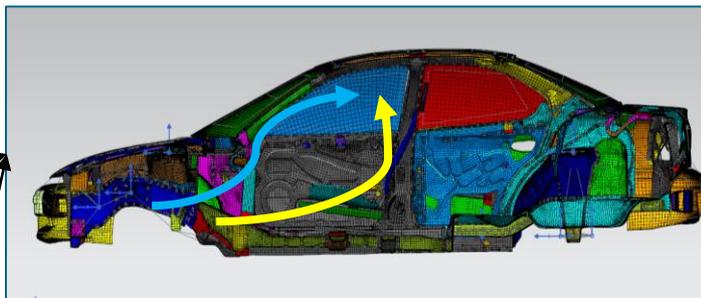


Operational surface vibrations
(Airborne noise)

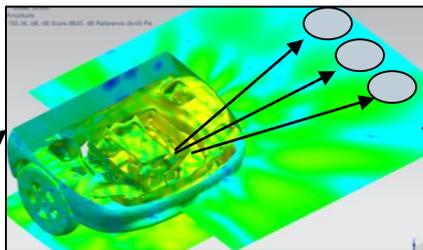


PATH TRANSFER

Vibro-Acoustic FRFs

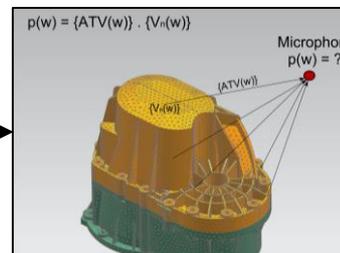


Acoustic FRFs SPL/ surface vibration



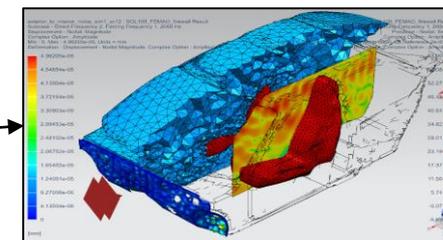
Installed condition

Free radiation condition

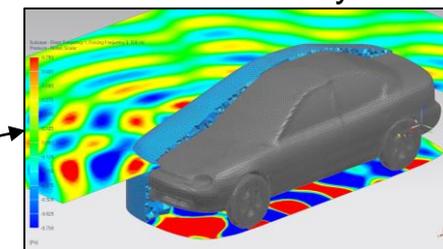


RECEIVER

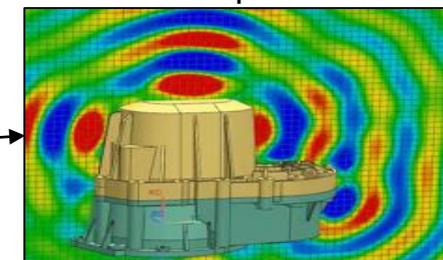
Cabin Powertrain Noise



Exterior Pass-By Noise



Ext. Component Noise

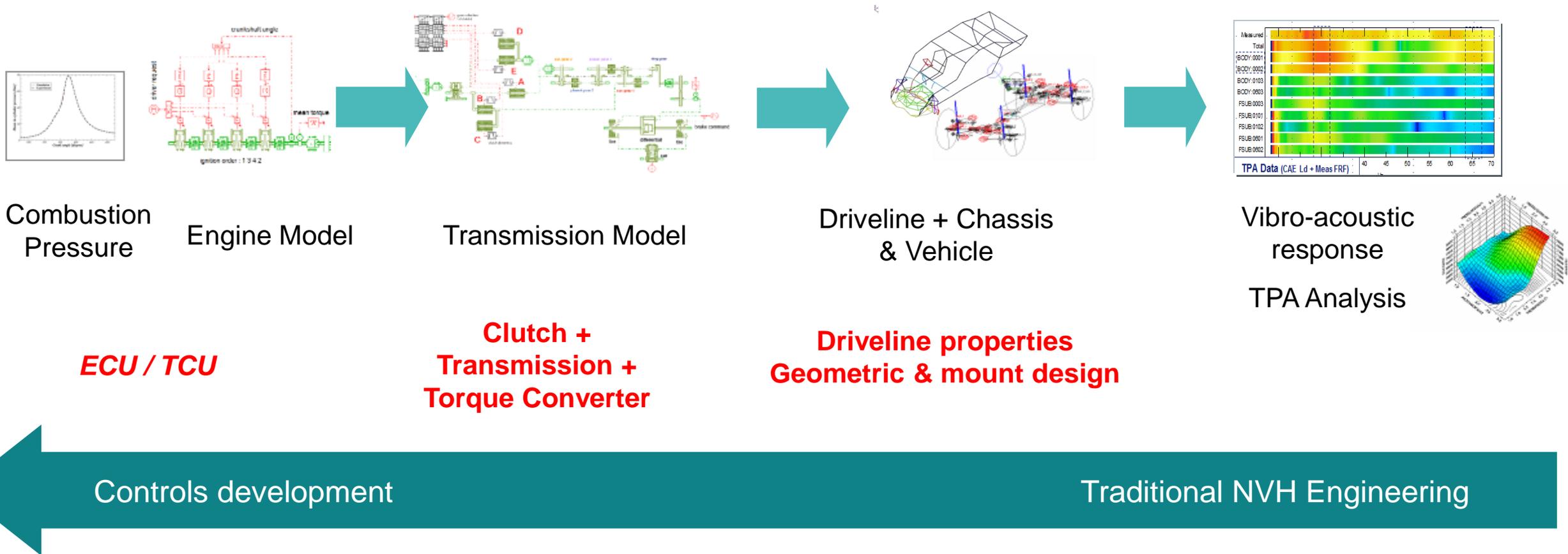


Model-based TPA

Application example: Low frequency driveline booming



Extending TPA to system simulation and controls development



Fahrzeugkomfort und Akustik durch Weiterentwicklungen der Transferpfadanalyse optimieren

Einführung

Klassische Methoden der TPA

TPA im Zeitbereich

Komponenten-TPA

Modellbasierte TPA

Zusammenfassung + Ausblick



Transfer Path Analysis Process

Complete process supported on one single platform

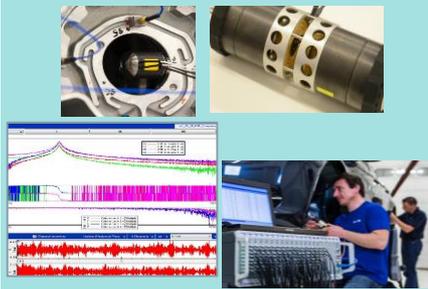
SIEMENS

Ingenuity for life

Simcenter
Testlab 2019.1

Testing

FRF measurements



Accurate FRF and NTF measurements for load identification and contribution analysis

Simcenter Structures Acquisition

Operational measurements



Operational measurements for operational load identification

Simcenter Signature Acquisition

Load Identification

$$E^l(\omega) = K^l(\omega) * \frac{-\omega_s}{(g^{st}(\omega) - g^{bl}(\omega))}$$



$$\begin{bmatrix} F_1(\omega) \\ F_2(\omega) \\ \vdots \\ F_n(\omega) \end{bmatrix} = \begin{bmatrix} H_{11}(\omega) & H_{12}(\omega) & \dots & H_{1n}(\omega) \\ H_{21}(\omega) & H_{22}(\omega) & \dots & H_{2n}(\omega) \\ \vdots & \vdots & \ddots & \vdots \\ H_{n1}(\omega) & H_{n2}(\omega) & \dots & H_{nn}(\omega) \end{bmatrix}^{-1} \begin{bmatrix} a_1(\omega) \\ a_2(\omega) \\ \vdots \\ a_n(\omega) \end{bmatrix}$$

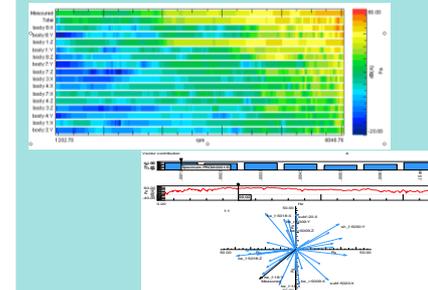


Load identification using the appropriate technique

Simcenter Transfer Path Analysis

Analysis

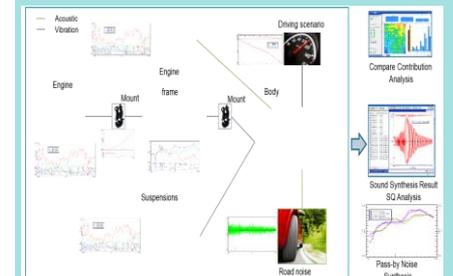
Contribution Analysis



Load identification and validation based on different techniques

Simcenter Transfer Path Analysis

Predictive Analysis



Predict full vehicle performance for each variant and load case

Simcenter Component Based TPA

Add
Simulation

Simcenter provides a fully integrated environment for streamlined work- and data flows