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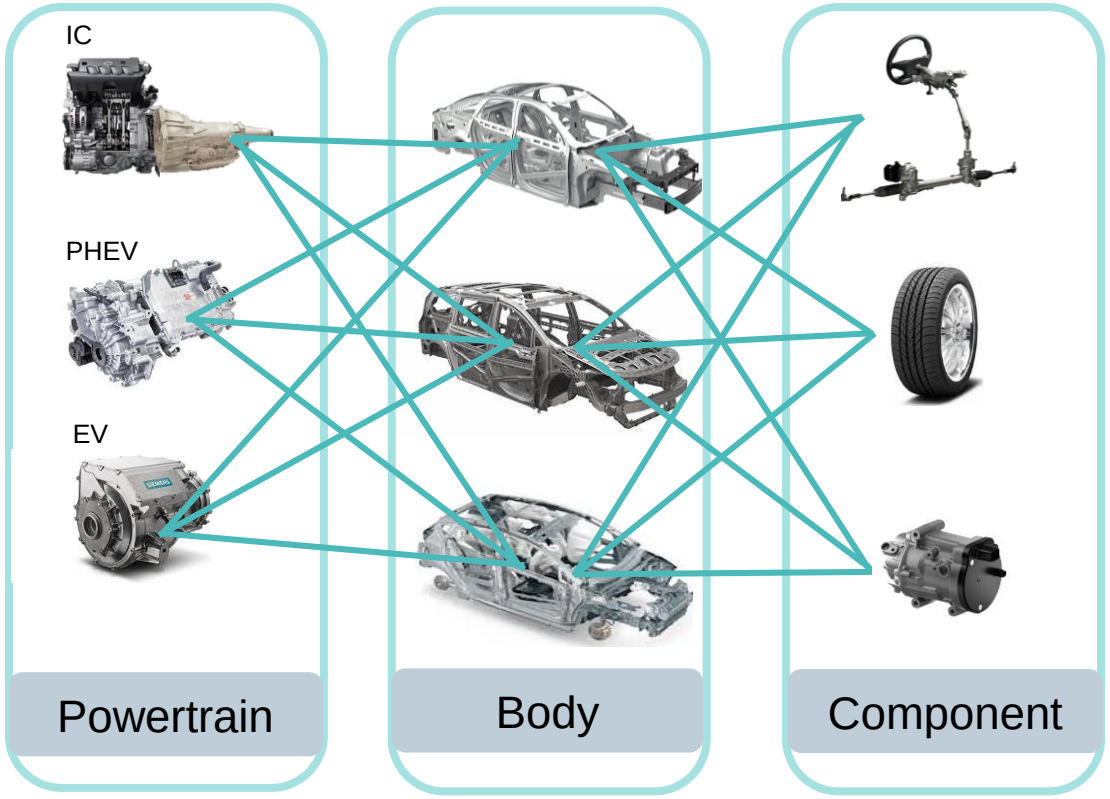
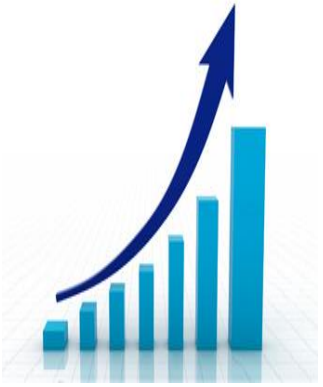
Component-based transfer path analysis

Your future-proof strategy for advancing NVH vehicle development

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

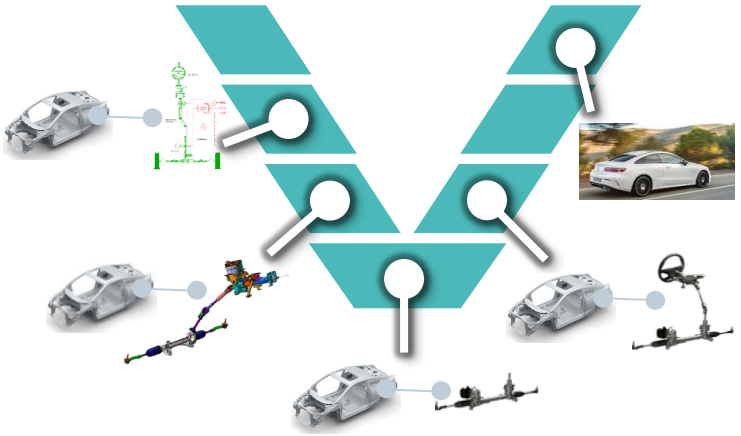


# of vehicle variants



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

Virtual Vehicle Prototyping



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

Front-loading vehicle level component NVH testing

Increasing complexity continuously challenges automotive OEM's and Suppliers

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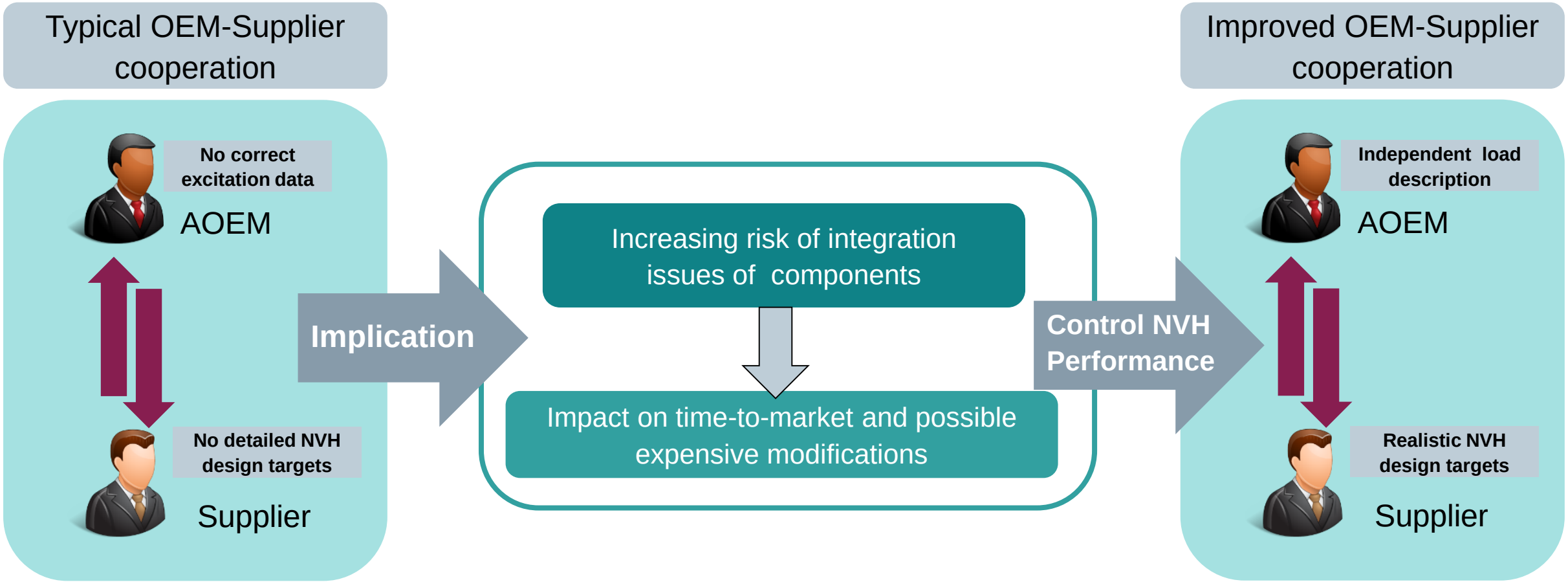

How to keep control of the NVH Performance at any stage of the development cycle?

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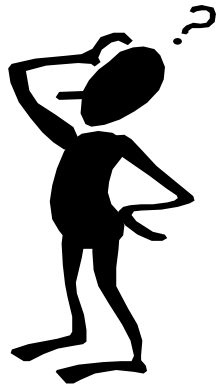
Can we provide a method that addresses all these challenges?



YES, WE CAN!
Component-based TPA

Component based TPA

Speeding up the development cycle by combining testing and simulation

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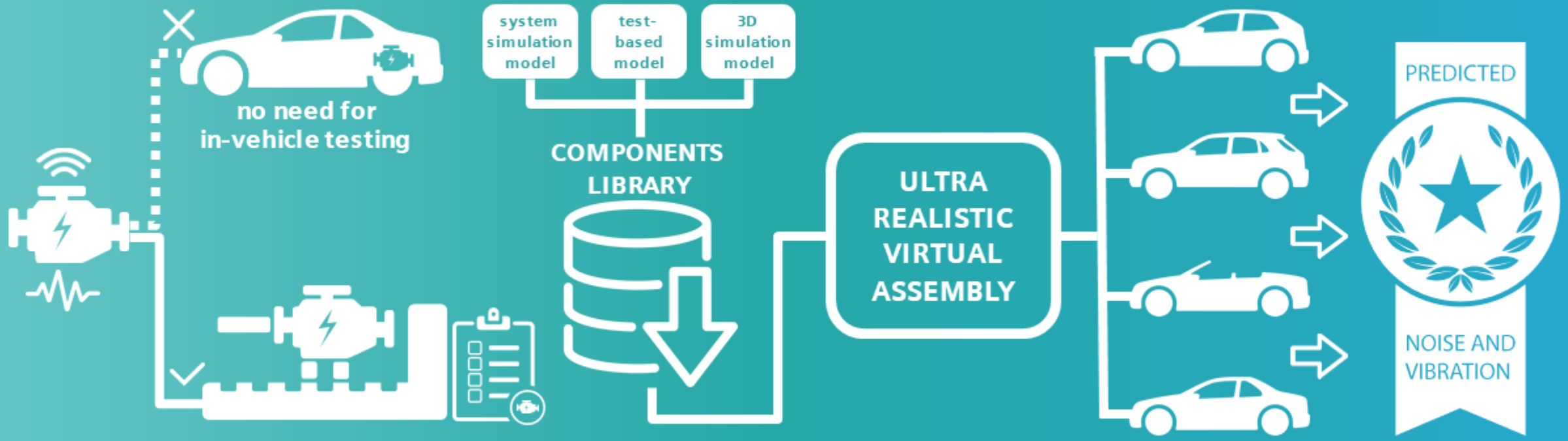

identify key components likely to contribute to noise and vibration issues

isolate components for high quality test bench data collection and independent load characterisation

create a test and simulation based components library

increase realism through seamless integration of system simulation, 3D and test models

combine the component models throughout the different vehicle variants

asses the product's behavior before prototyping

Classical Transfer Path Analysis

Source-transfer-receiver approach

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Engine

HVAC

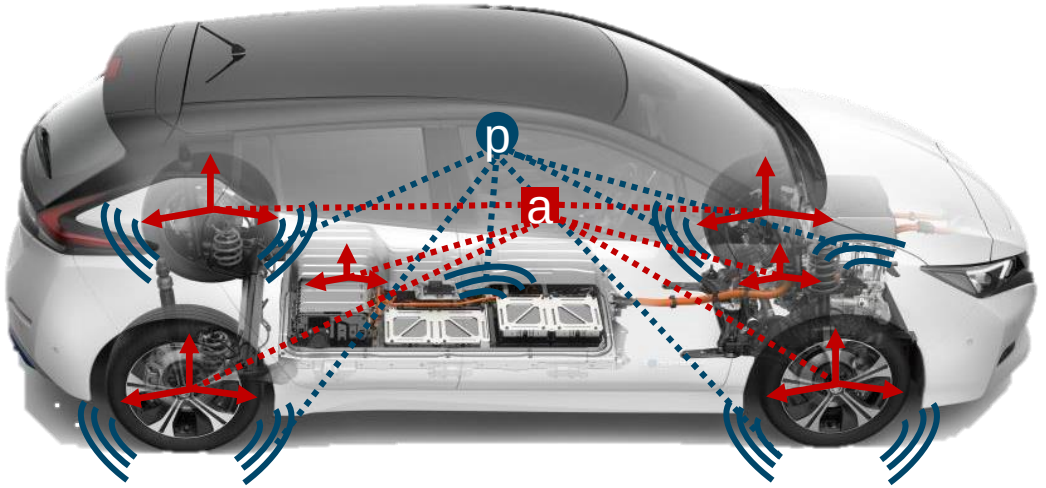
E-motor

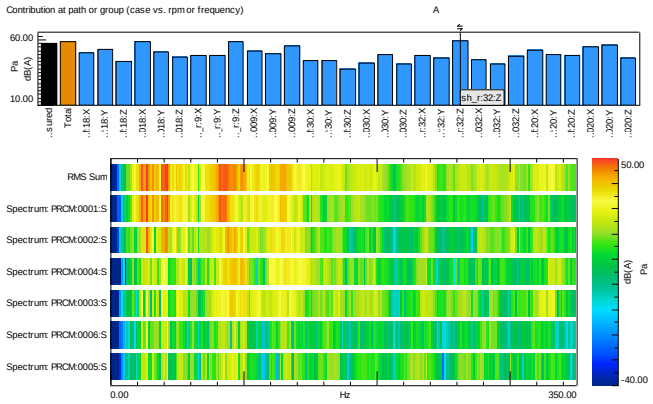
Wiper-motor

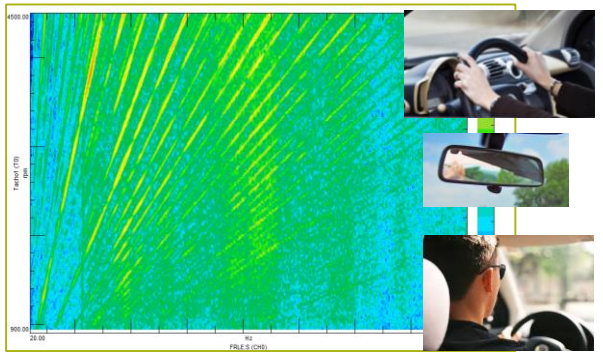
Transmission

Tyres

EPS







Source (F_i,Q_j) — **X** — **Transfer (NTF)** — **=** — **Receiver (y_k)**

Source-Receiver interaction

Exchange of contact forces

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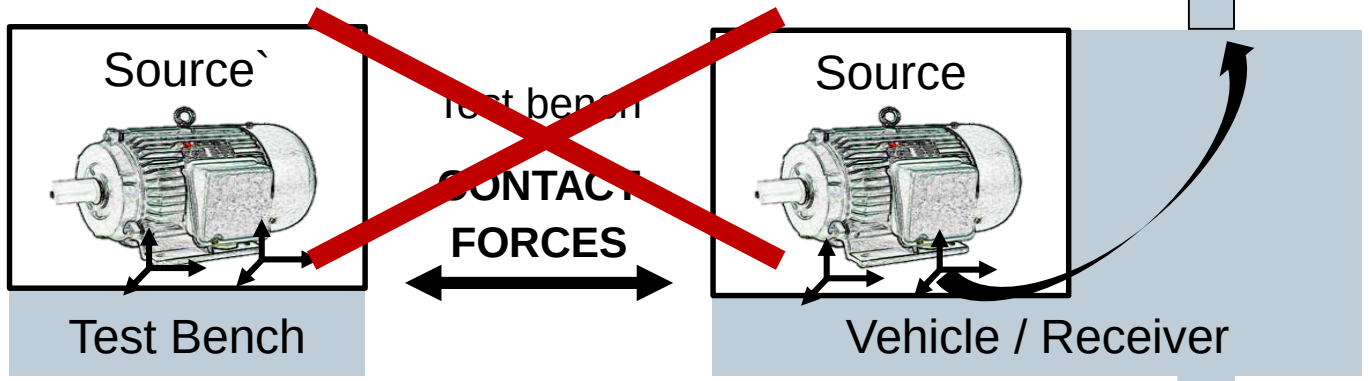
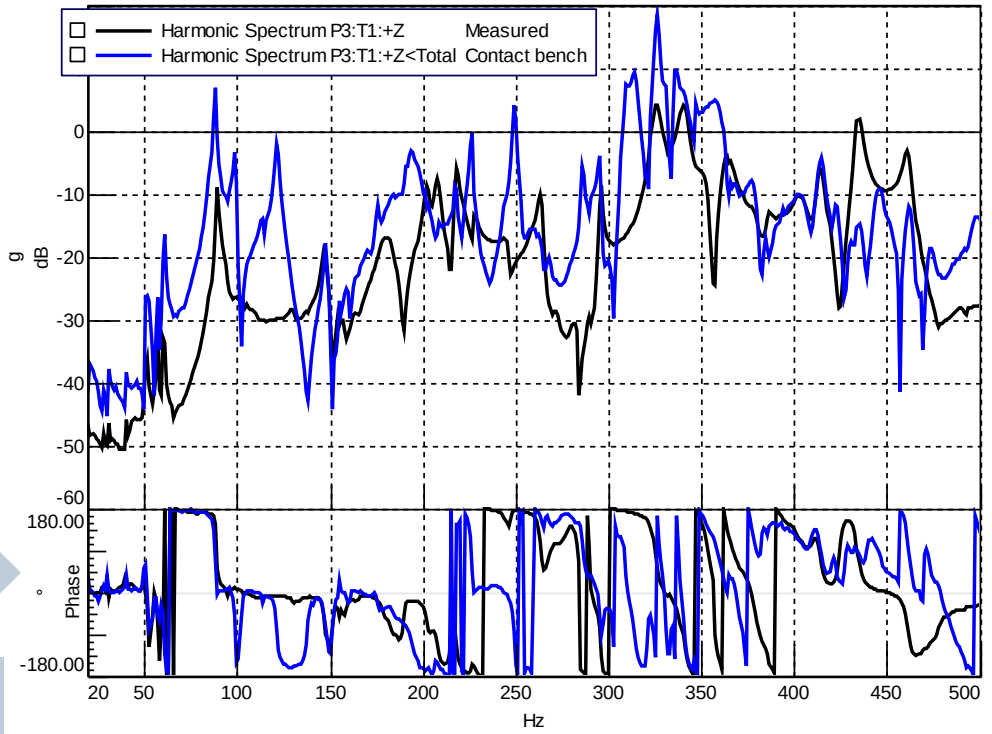
Supplier

AOEM

Predict Target Response





Predicted target deviates from measured target!

Source-Receiver interaction

Exchange of Independent loads

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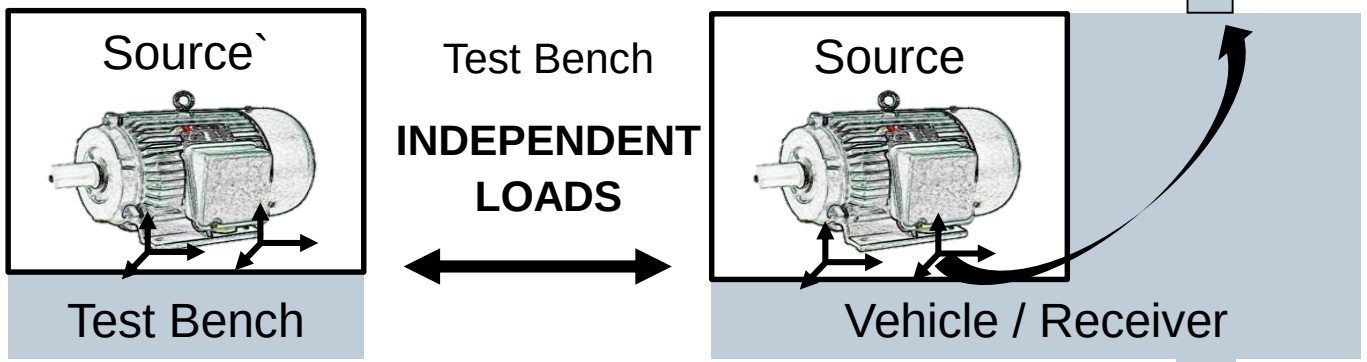
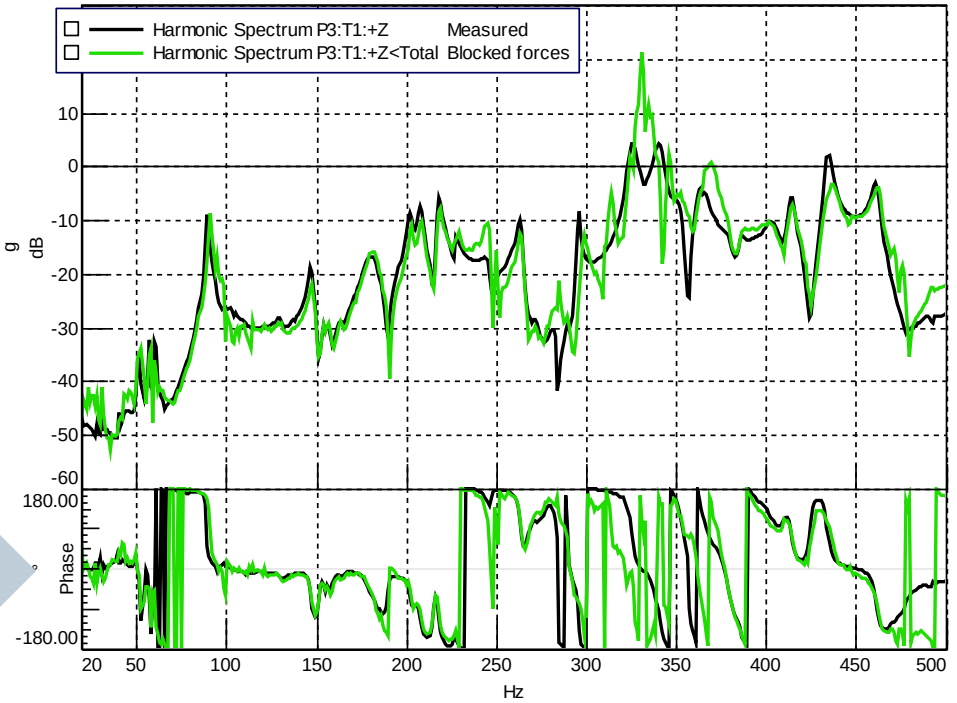
Supplier

AOEM

Predict Target Response





Predicted target matches measured target!

Component Based Transfer Path Analysis

Predict full system level performance

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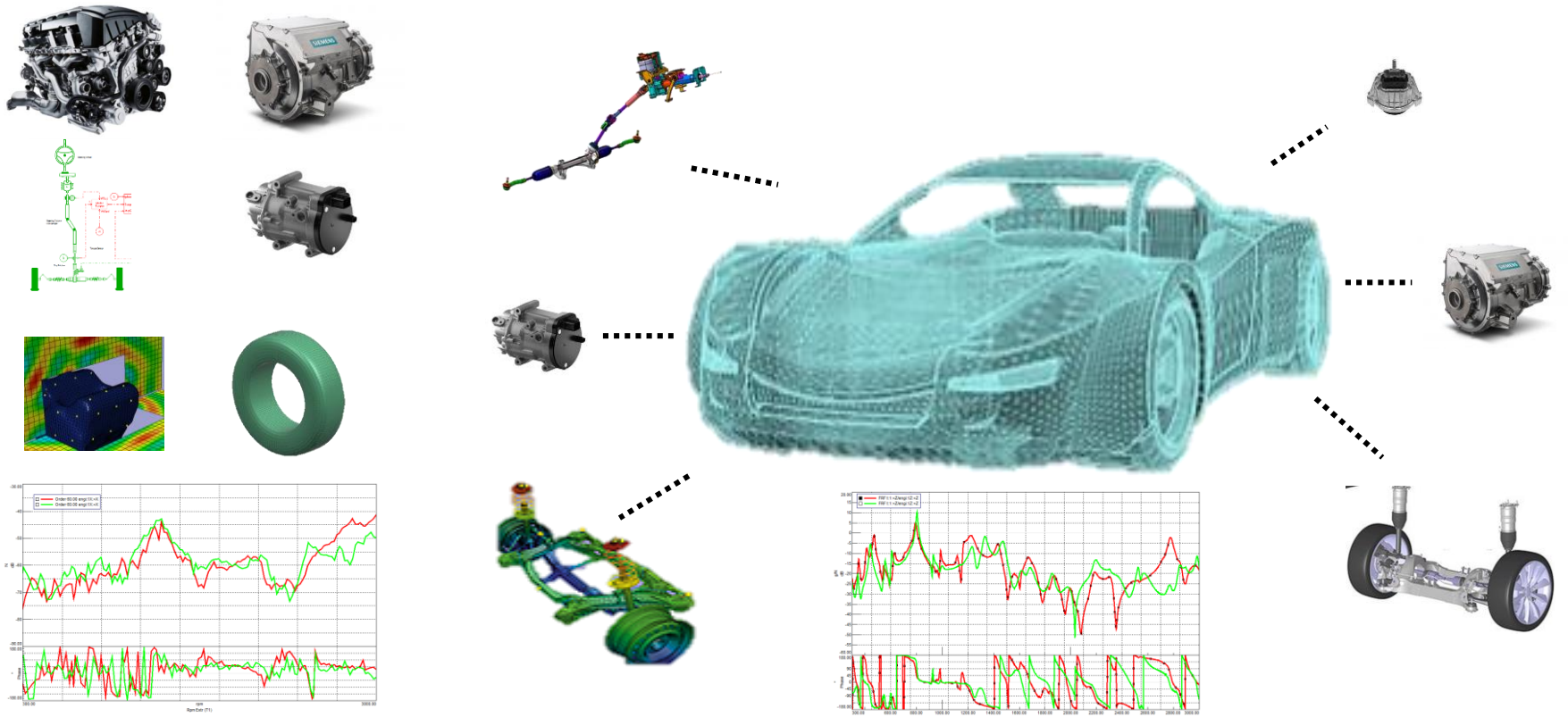
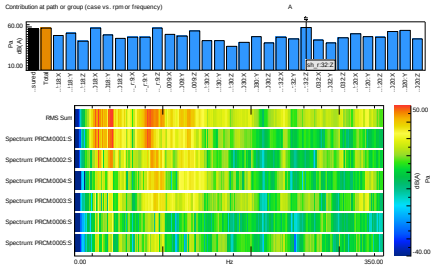
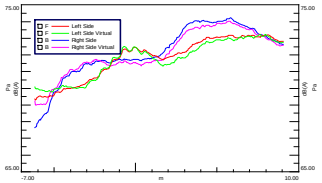


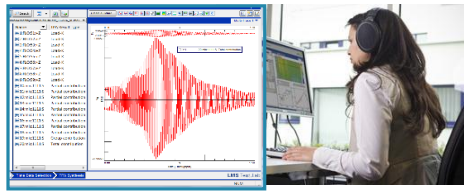
Contribution analysis



Pass-by Noise



Sound synthesis



Step 1: Independent loads (F_{bl},Q) — **X** — **Step2: Virtual Assembly (FRF, K)** — **=** — **Step3: Prediction(y_k)**

Component Based TPA

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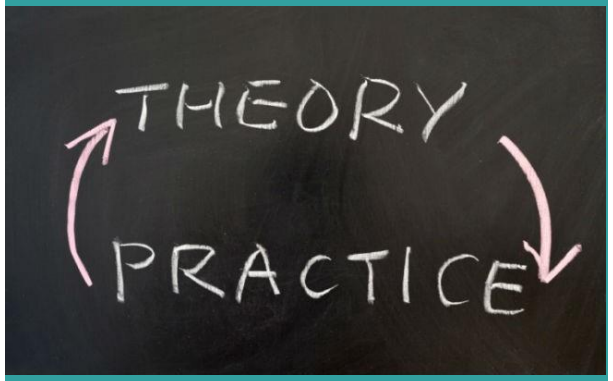
Independent Source characterization

Theory of method

Blocked Forces as Independent source description

Measurement challenges



From theory to measurements

Extensive mathematics require accurate data

Application Examples

Deal with the subsystem specific challenges

Difference in Test benches & methodologies

Full Vehicle NVH Synthesis

Combining all systems & predict full vehicle NVH performance

Component Based TPA

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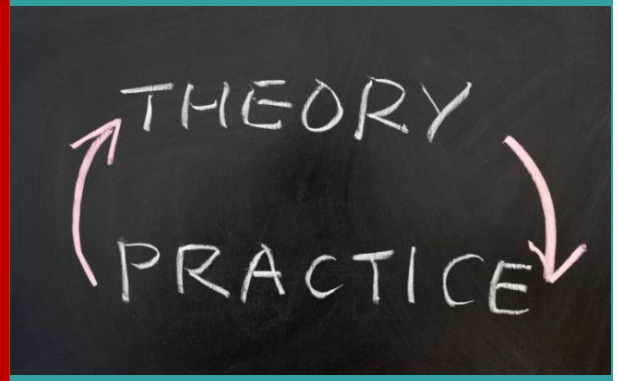

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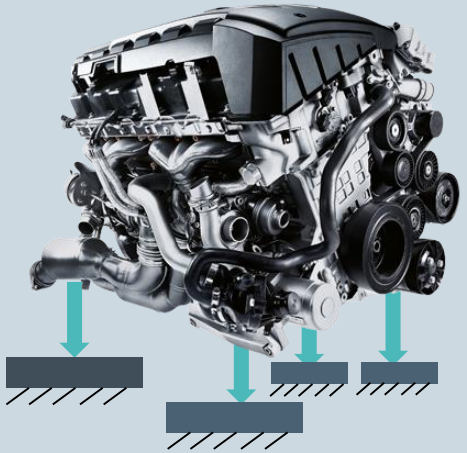
Structure-borne:

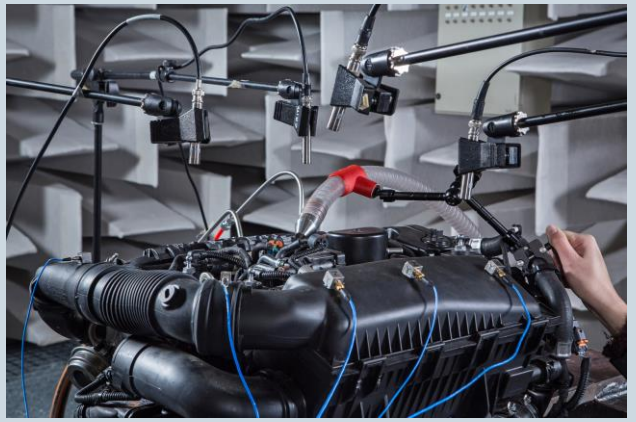
Blocked Forces

Free Velocities



Airborne:

Volume Velocities



Component-based TPA

Step1: Source characterization - *Structure Borne*

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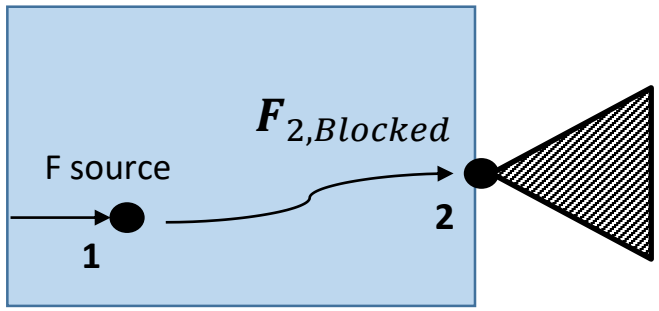
Three possible methodologies to obtain independent source description

1. Blocked Force

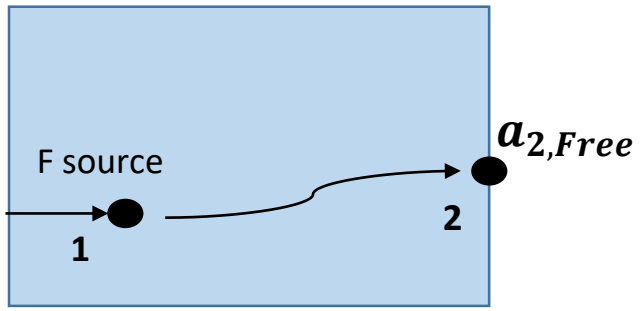
Source A



Rigid test rig → Most times not possible

2. Free Velocity

Source A

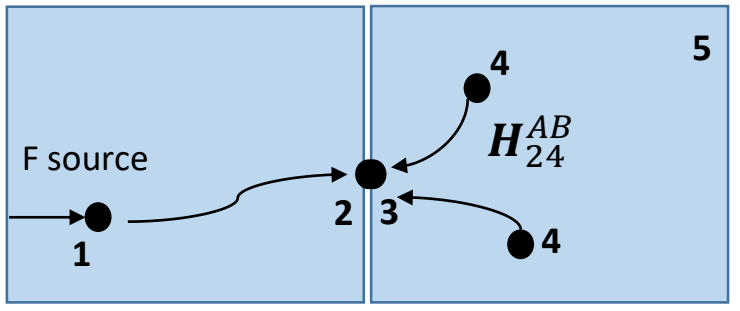


$$[H_{22}^{A}]^{-1} a_{2,Free} = F_{2,Blocked}$$

Source in free free conditions ISO 9611

3. In-Situ TPA

Source A | Receiver B



$$F_{2,Blocked} = [H_{24}^{AB}]^{+} a_4$$

Any receiver is valid ISO 20270

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

Contact force vs. Blocked force

Different measurement setup for local FRF

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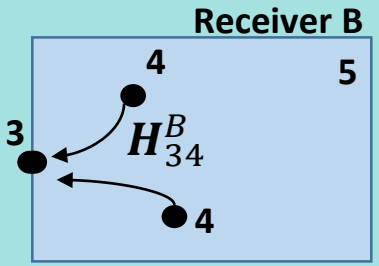
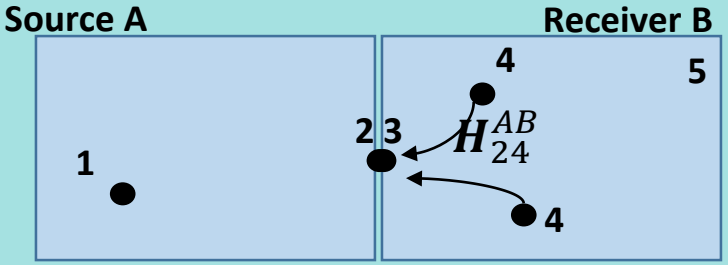
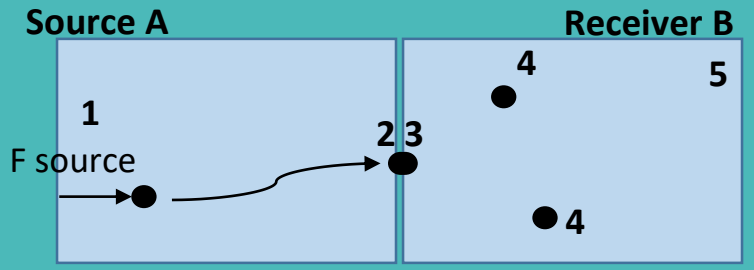
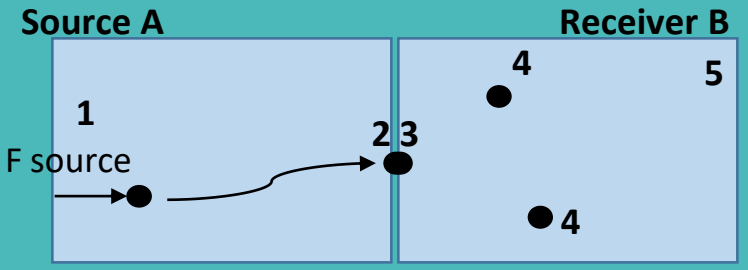
	Classic TPA Determination **contact forces**		Blocked Forces TPA Determination **blocked forces**
1. Local FRF for load identification		≠	
2. Operational measurements		=	
3. Force Identification	$F_{3,Contact} = [H_{34}^{B}]^{+} a_4$	≠	$F_{2,Blocked} = [H_{24}^{AB}]^{+} a_4$

Structure borne application example

Steering system integration

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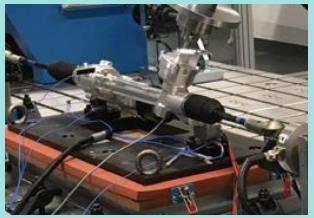
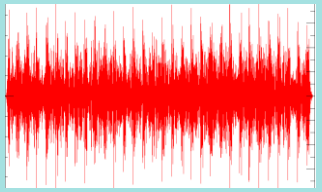
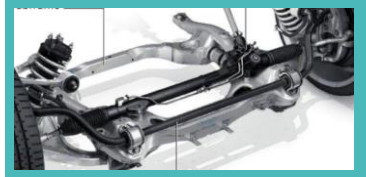
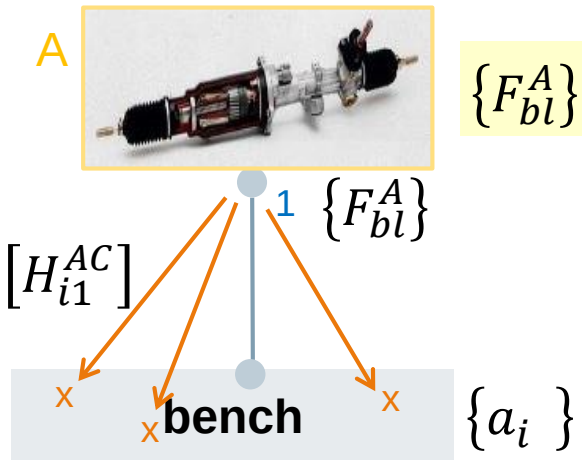
Source Mechanism	Invariant Source Synth. Model	Sub-Receiver	Receiver
 Steering System	 Blocked Forces & Impedances Mount Pos.	 Subframe FEM/TEST FRF	 Body FEM/TEST FRF

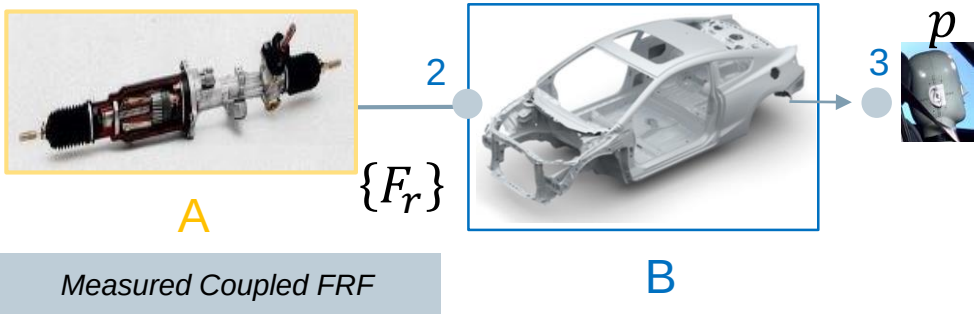
STEP 1: Source Characterization



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

$\{a_i\}$

STEP 2: Full Vehicle Prediction



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

1. In-Situ TPA – Apply Matrix Inversion: Blocked Forces = source characterization

Component-based TPA

*Step2: Target p*rediction using Frequency based sub-structuring (FBS)

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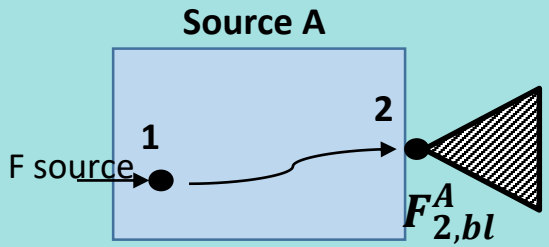
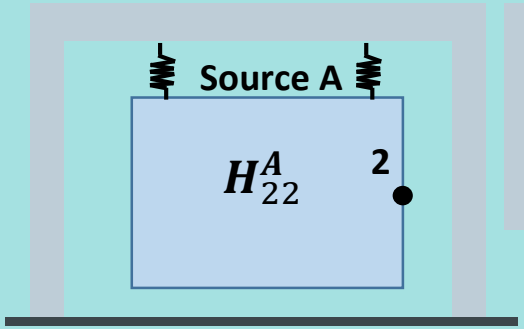
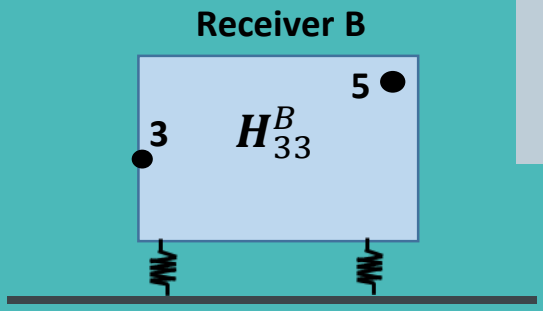
1. **Source A:**
   a. Blocked Force $F^A_{2,bl}$
   b. Inertance matrix H^A_{22}





Free-Free or pre-load condition

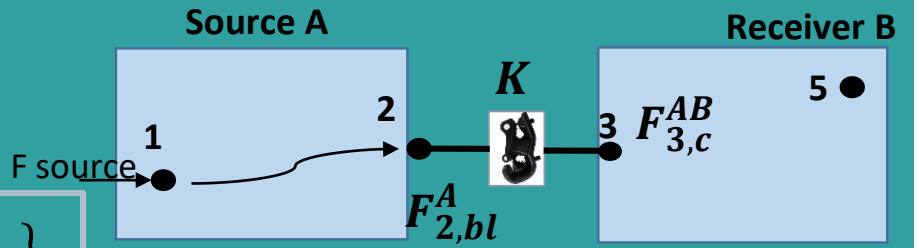
2. Receiver B:
   a. Inertance matrix H^B_{33}
   b. Noise Transfer Function $[H^B_{53}]$



Realistic boundary condition

3. Target prediction using blocked forces $F^A_{2,bl}$
   a. Mount stiffness K (not needed for rigid connections)
   b. FBS

$$\{P^{AB}_5\} = [H^B_{53}] * [H^A_{22} + H^B_{33} + K^{-1}]^{-1} * [H^A_{22}] * \{F^A_{2,bl}\}$$



Structure borne application example

Steering system integration

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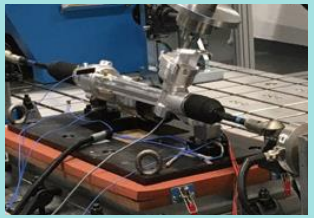
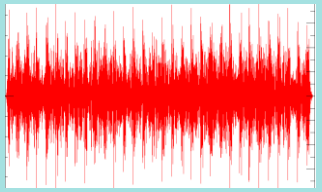
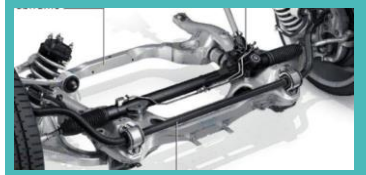
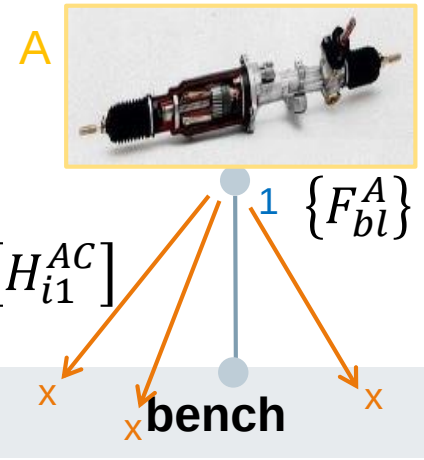
Source Mechanism	Invariant Source Synth. Model	Sub-Receiver	Receiver
 Steering System	 Blocked Forces & Impedances Mount Pos.	 Subframe FEM/TEST FRF	 Body FEM/TEST FRF

STEP 1: Source Characterization



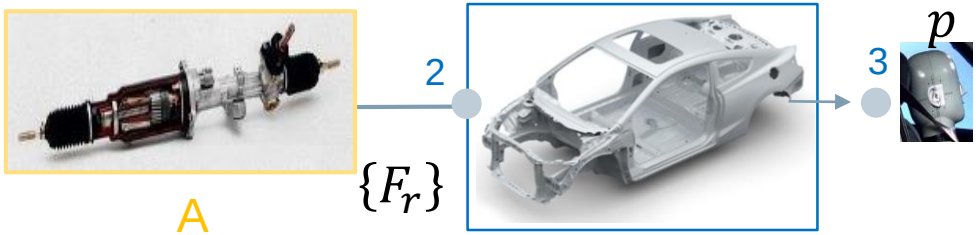
$$\{F_{bl}^A\} = [H_{i1}^{AC}]^{-1} * \{a_i\}$$

$\{a_i\}$

1. In-Situ TPA – Apply Matrix Inversion: Blocked Forces = source characterization

$\{F_{bl}^A\}, H_{11}^A$

STEP 2: Full Vehicle Prediction



Calculate Coupled FRF

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

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

2. Component Based TPA – Apply FBS Substructuring for load prediction

Component Based TPA

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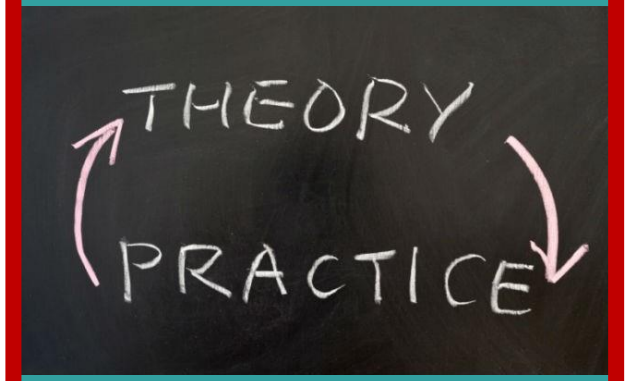
Independent Source characterization

Theory of method

Blocked Forces as Independent source description

Measurement challenges



From theory to measurements

Extensive mathematics require accurate data

Application Examples

Deal with the subsystem specific challenges

Difference in Test benches & methodologies

Full Vehicle NVH Synthesis

Combining all systems & predict full vehicle NVH performance

Component Based TPA: required tools

'extensive mathematics require accurate data'

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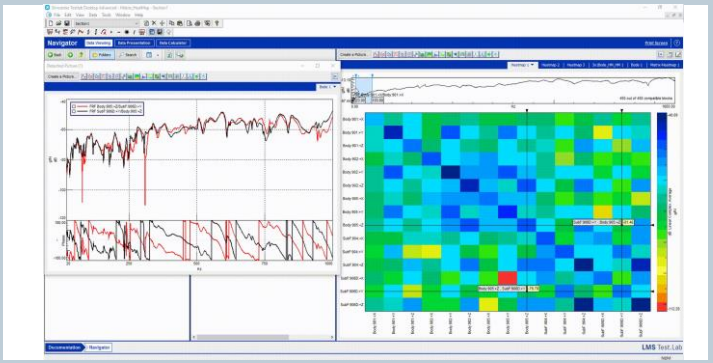
Accuracy

- hard to reach location
- angle & position accuracy
- repeatability / low noise / high power
- large frequency range from 5Hz -10kHz

Dedicated FRF shaker excitation - engineered for TPA measurement

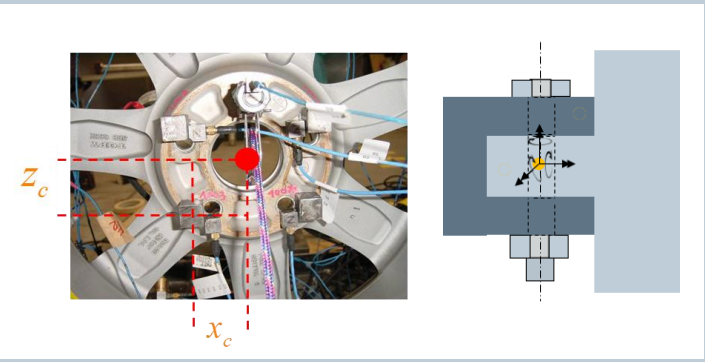
Validation



- reciprocity / linearity
- directions errors / consistency
- driving point behavior
- repeatability

Use the **Matrix heatmap** to instantly verify large datasets

Completeness



- FRF required at exact connection center – assuming local rigidity
- 6DOF FRF description of the connection is required for completeness

Reduce the FRF's to the connection center using **Virtual point transformation**

Virtual Point Transformation (VPT)

Accurate FRFs at interface connection points

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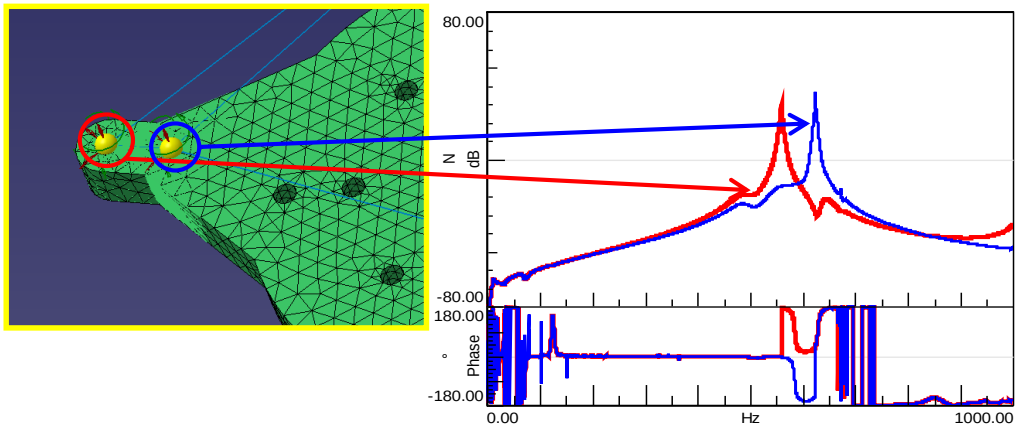
Challenge:

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

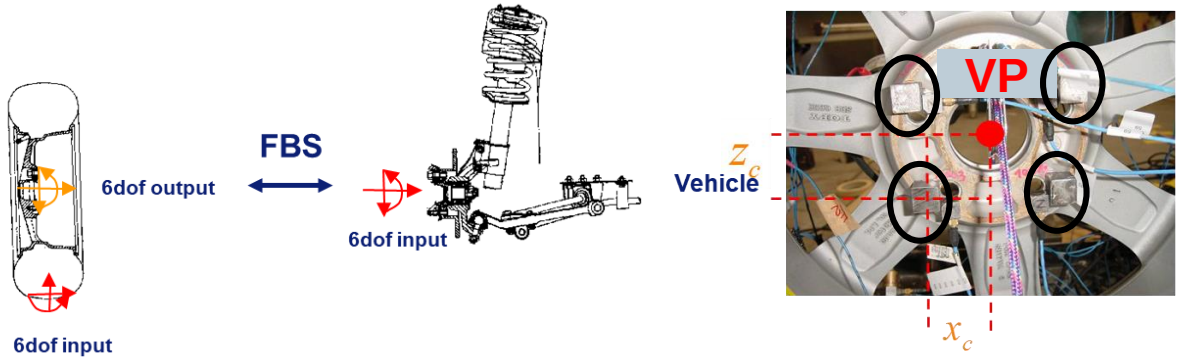
Solution:

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

VPT for correct blocked force estimation



VPT for correct assembly using FBS



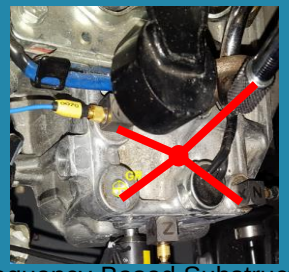
Virtual Point Transformation (VPT)

Application examples

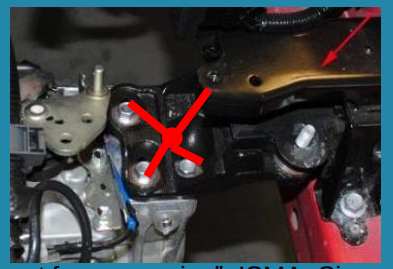
SIEMENS
Ingenuity for life

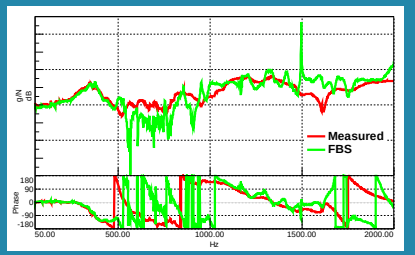
Transmission
VPT for improving FBS

TRANSMISSION



T/M BRACKET

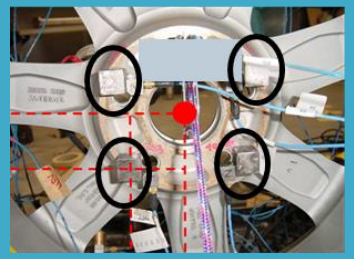




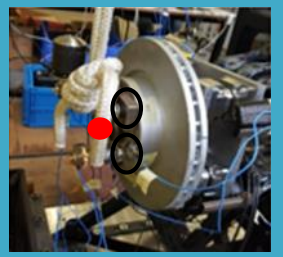
Source:" A Frequency-Based Substructuring approach to engine mount bracket performance assessment for gear noise", ISMA Siemens,Toyota Motor Europe 2020

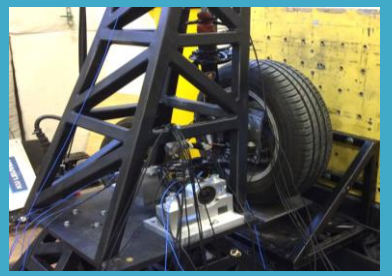
Road Noise
VPT for spindle forces/moments and FBS

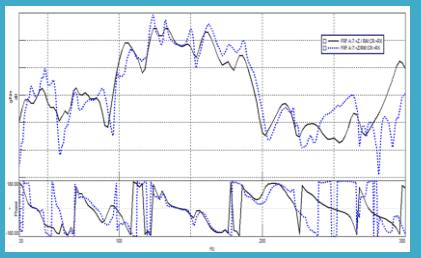
TIRE/WHEEL



SUSPENSION



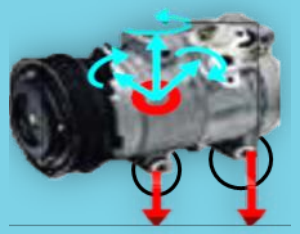




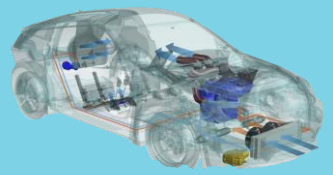
Source:" Structure-Borne Prediction on a Tire-Suspension Assembly Using Experimental Invariant Spindle Forces", SAE 2019 DOI: 10.4271/2019-01-1541

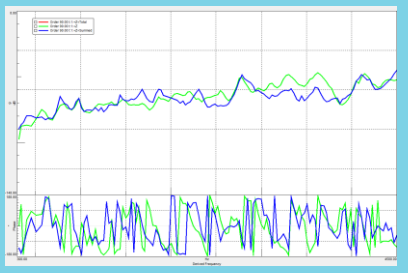
HVAC
Force reduction for improved prediction

COMPRESSOR



CAR BODY





Component Based TPA

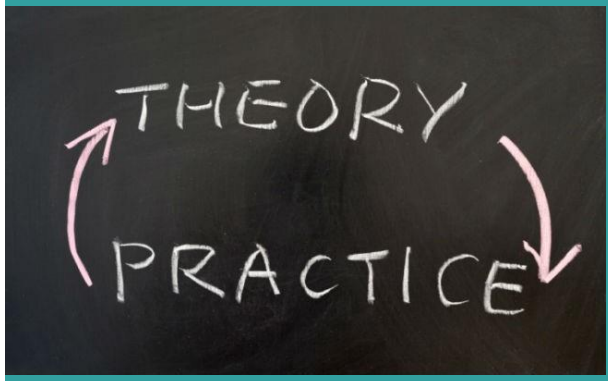
SIEMENS
Ingenuity for life

Independent Source characterization

Theory of method

Blocked Forces as Independent source description

Measurement challenges



From theory to measurements

Extensive mathematics require accurate data

Application Examples

Deal with the subsystem specific challenges

Difference in Test benches & methodologies

Full Vehicle NVH Synthesis

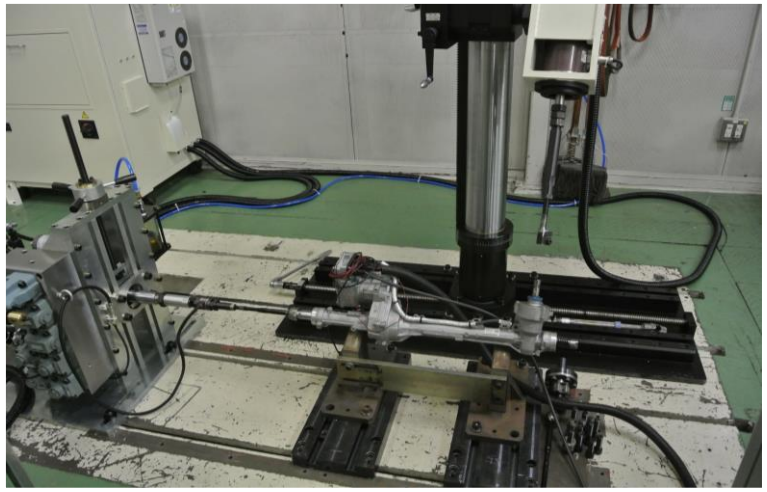
Combining all systems & predict full vehicle NVH performance

Hitachi AMS – Steering systems

Estimating in-vehicle noise of EPS using test bench

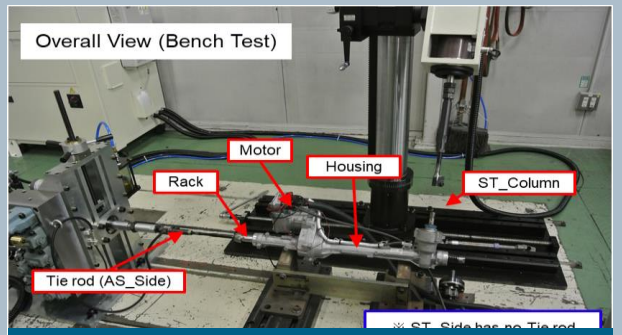
HITACHI
Inspire the Next

SIEMENS
Ingenuity for life

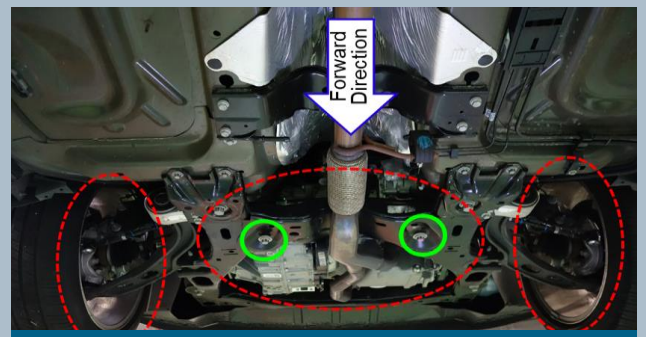


- **More realistic design targets for components**
- **Appropriate evaluation method at component prototype phase**
- **Predict in-vehicle noise/vibration using component based TPA method**

Development Component Based TPA methodology for NVH assessment

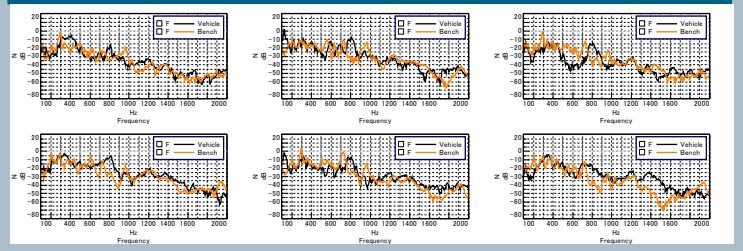


Test bench condition

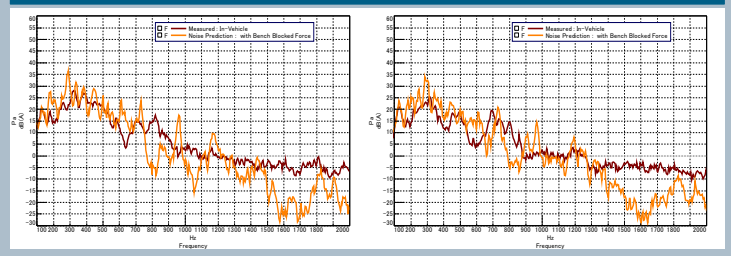


Vehicle condition

Blocked Force comparison



In-vehicle Noise prediction



- **Test bench identified blocked forces correlate with vehicle blocked forces**
- **Predicted cabin noise using test bench blocked forces well up to 1500Hz**

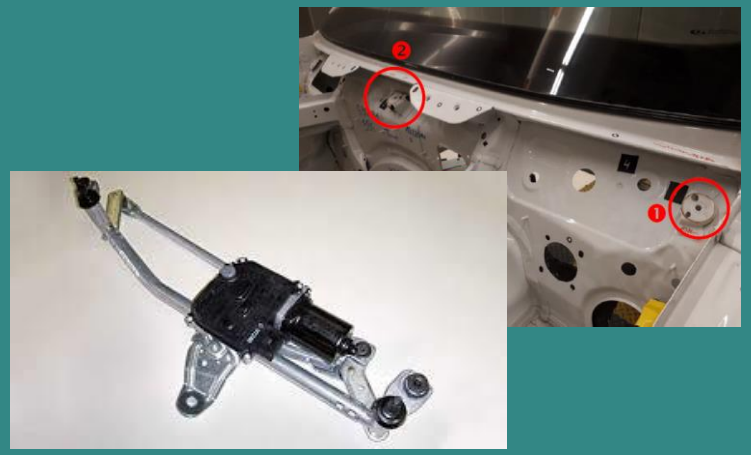
Aoi Nakanome Hitachi AMS, 2019 Simcenter Conference Amsterdam

Automotive OEM – Wiper System

Derive full vehicle structure-borne noise prediction from test rig

SIEMENS
Ingenuity for life

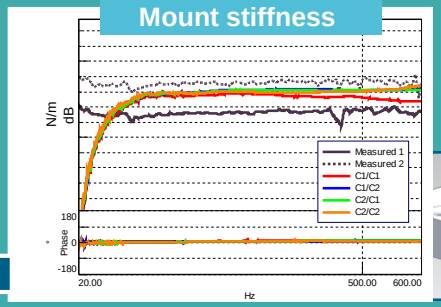
Identification of blocked forces on Mockup

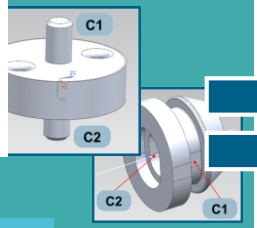


→ Source in operation: wiper system at 35 cpm.
→ Blocked forces calculated using in-situ TPA on dedicated test rig – matrix inversion.

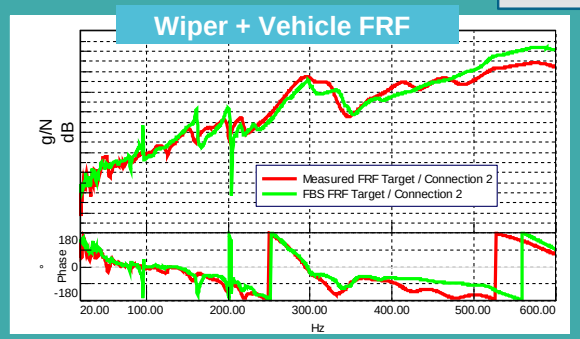
Full vehicle assembly from component level testing

Mount characterization

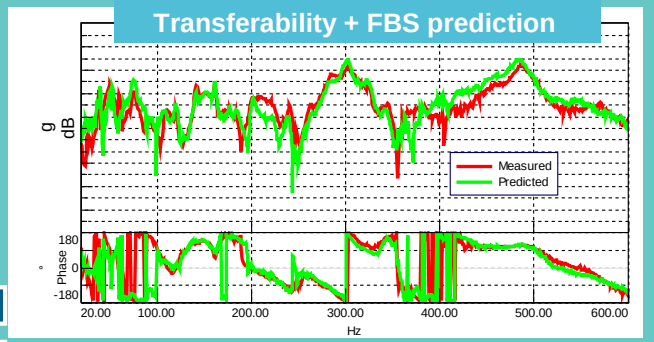




Substructuring



Prediction of target response



→ Performance evaluation
→ using ISO/CD 21955 for prediction
→ Identification of path contribution
→ Input for target setting
→ What if analyses:
- Sensitivity to mount stiffness
- Receiver modification.

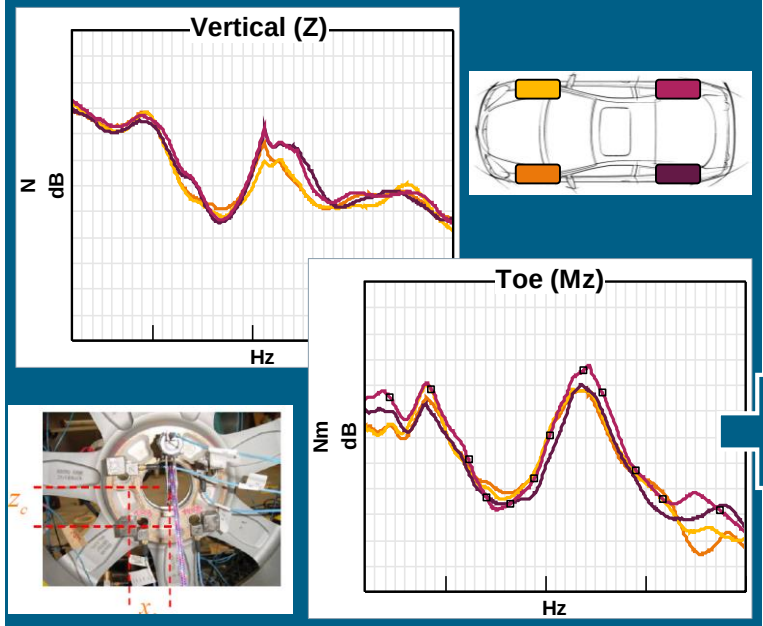
Ortega, Bianciardi, Corbeels, Ullmann, Desmet, MOUNT CHARACTERIZATION ANALYSIS IN THE CONTEXT OF FBS FOR COMPONENT-BASED TPA ON A WIPER SYSTEM, , FA 2020, Lyon, Siemens, KULeuven, BMW

Automotive OEM – Road Noise

Wheel center blocked forces

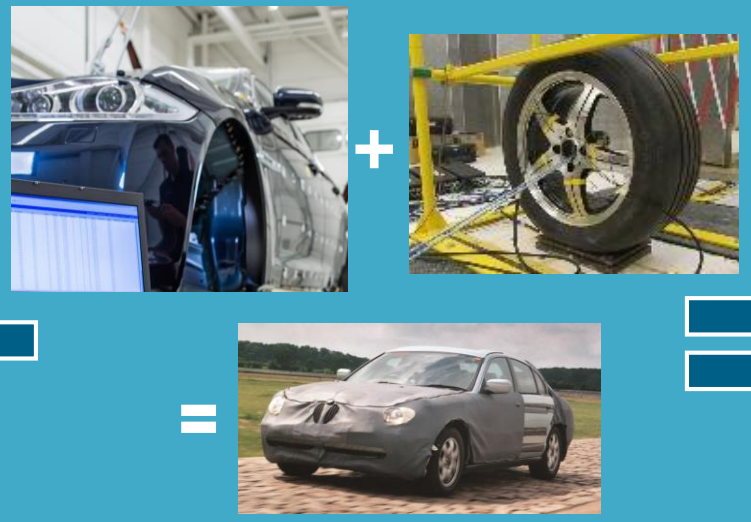
SIEMENS
Ingenuity for life

Identification of blocked forces



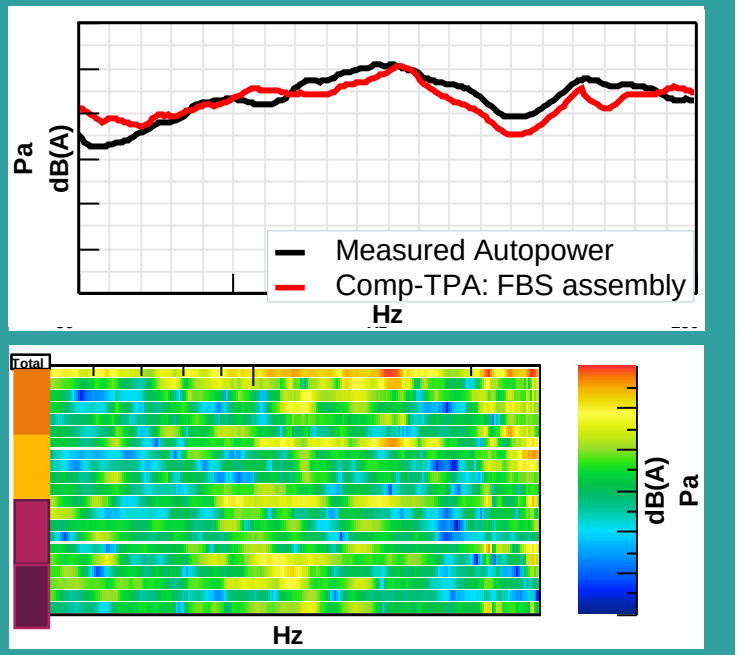
- Invariant forces: receiver independent
- Transferable between receiving structures

Full vehicle assembly from component level testing



- Independent characterization of source and receiver
- Virtual vehicle assembly

Prediction of target response



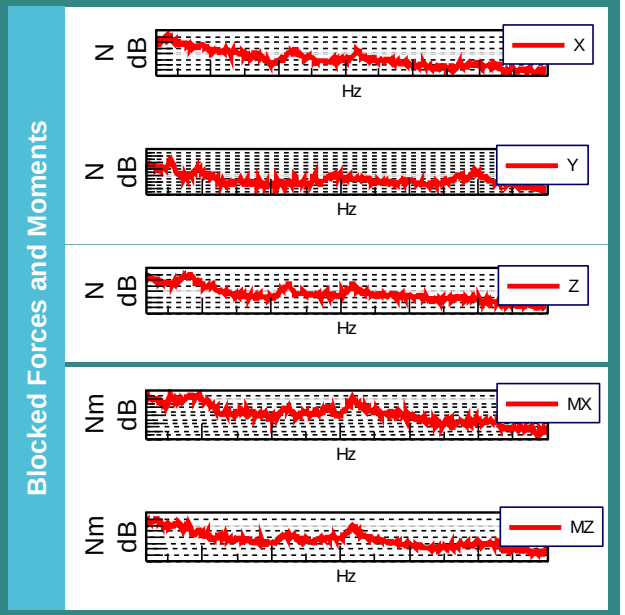
- Performance evaluation
- Identification of path contribution
- Input for target setting

Automotive Supplier – Tire manufacturer

Road noise – Wheel center blocked forces

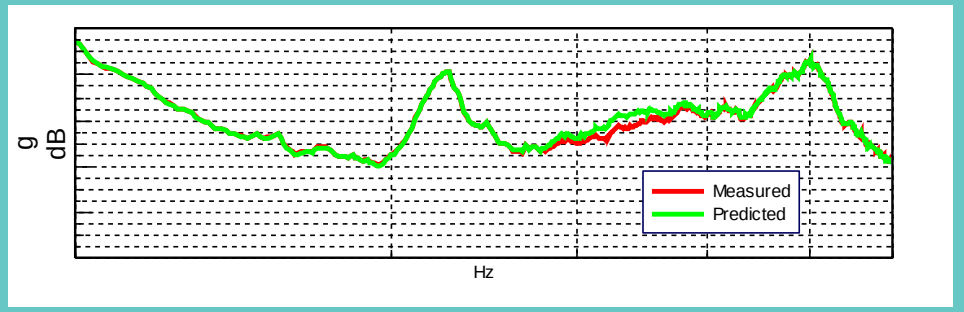
SIEMENS
Ingenuity for life

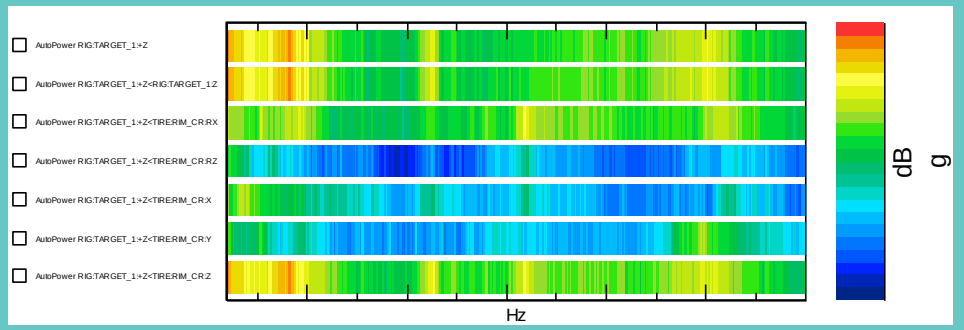
Identification of blocked forces on test rig



- Source in operation: 20 / 40 / 60 / 80 / 100 kph.
- Blocked forces calculated using in-situ TPA: matrix inversion using multiple integral shakers for FRF a
- Blocked forces measured on rigid test rig using force cell (usable only up to 300 Hz)

On board validation of target response on test rig





- **On-board validation**
- Identification of path contribution
- Input for realistc target setting & prediction
- Independent

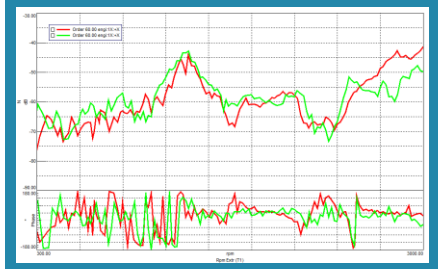
Component-based TPA

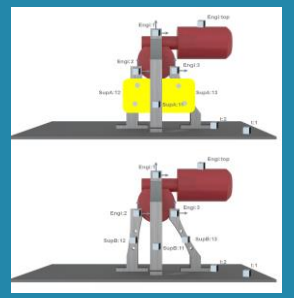
Electromotor blocked forces – Assembly vibration prediction

SIEMENS
Ingenuity for life

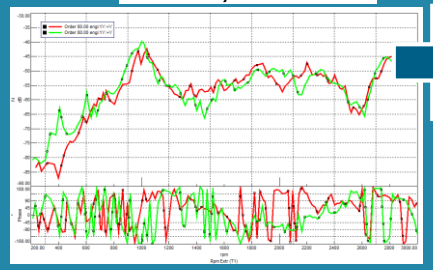
Identification of blocked forces

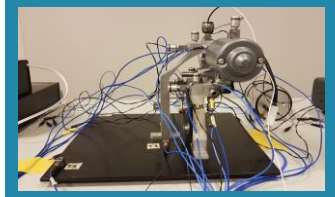
Order60, X-direction





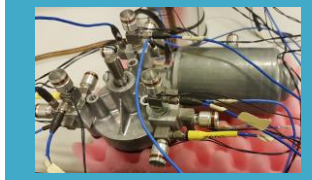
Order80, Y-direction





- Invariant forces: receiver independent
- Transferable between receiving structures
- High frequency up to 4.5kHz

System assembly from component level testing



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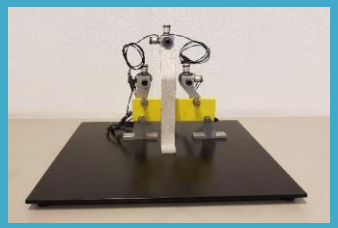

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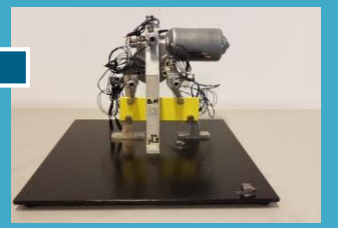
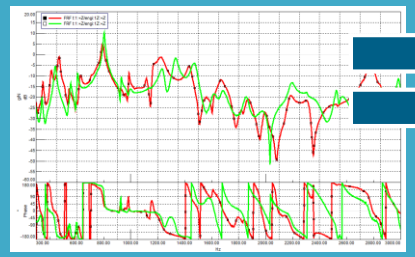
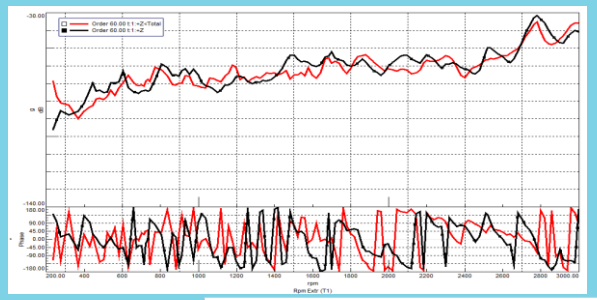
FBS vs Measured



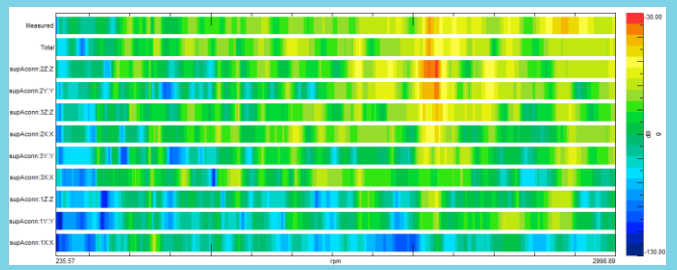


- Independent characterization of source and receiver
- Virtual vehicle assembly

Prediction of target response



Measured Order
Comp-TPA: FBS assembly



- Performance evaluation
- Identification of path contribution
- Input for target setting

Bianciardi, Corbeels, Choukri, HIGH FREQUENCY SOURCE CHARACTERIZATION OF AN E-MOTOR USING COMPONENT BASED TPA, SIA 2020, Siemens

Component Based TPA

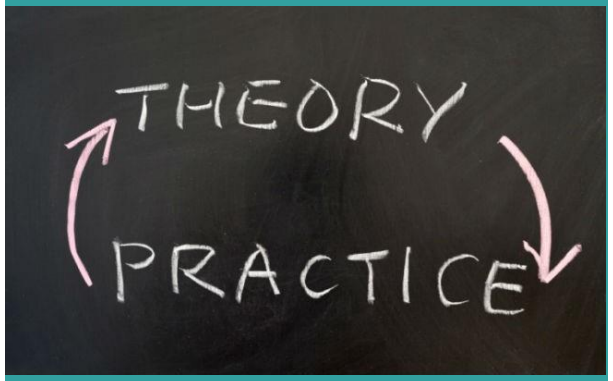
SIEMENS
Ingenuity for life

Independent Source characterization

Theory of method

Blocked Forces as Independent source description

Measurement challenges



From theory to measurements

Extensive mathematics require accurate data

Application Examples

Deal with the subsystem specific challenges

Difference in Test benches & methodologies

Full Vehicle NVH Synthesis

Combining all systems & predict full vehicle NVH performance

Component based TPA for full vehicle NVH assessment

Model Based Development for NVH – Concept

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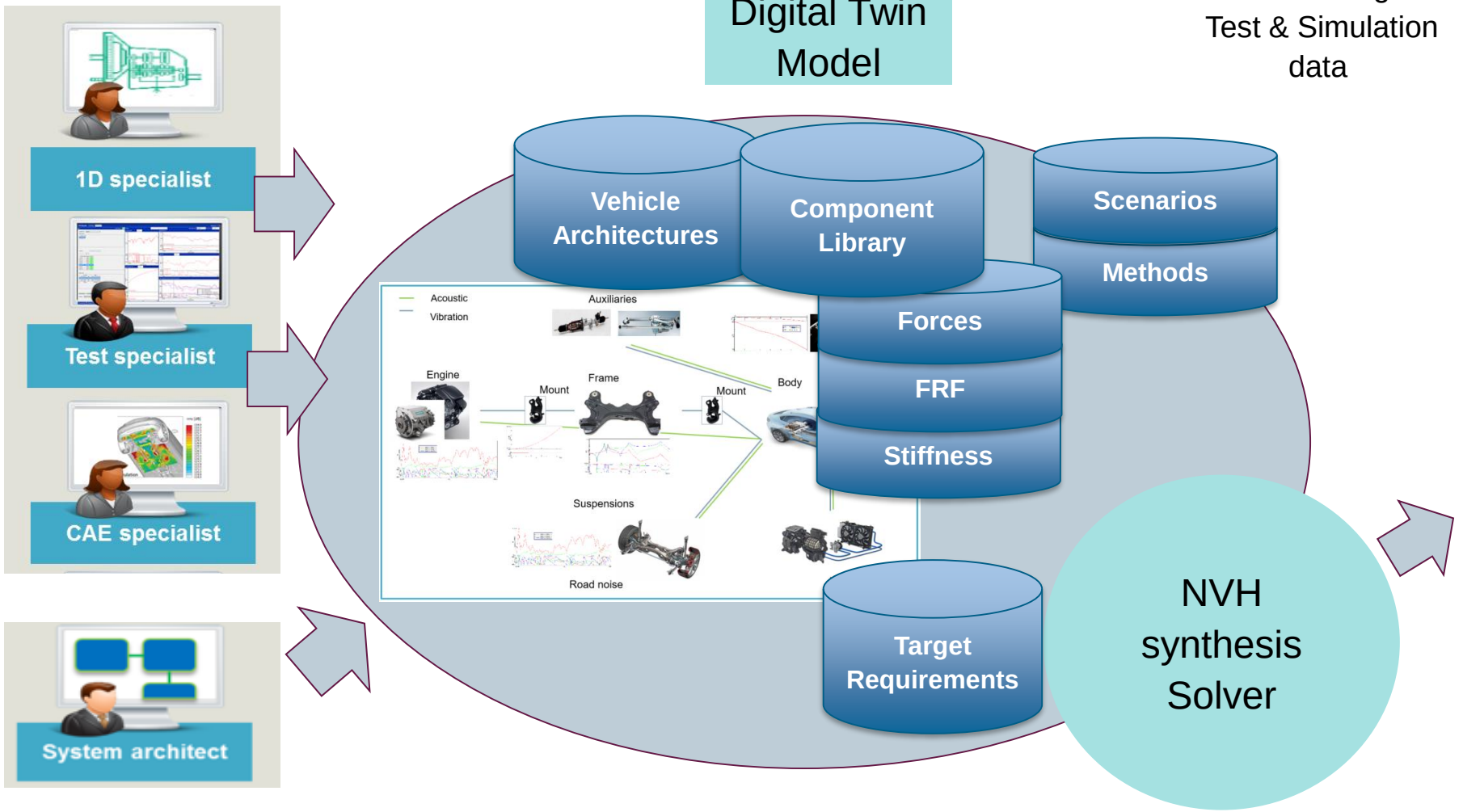
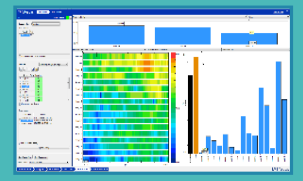
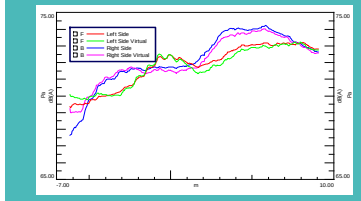
Ingenuity for life



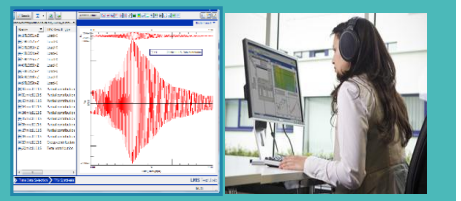
Compare Contribution Analysis



Pass-by Noise Synthesis



Sound Synthesis Result



NVH Driving Simulator Evaluation

Simcenter Testlab NVH Synthesis

Model Based Development for NVH

SIEMENS
Ingenuity for life

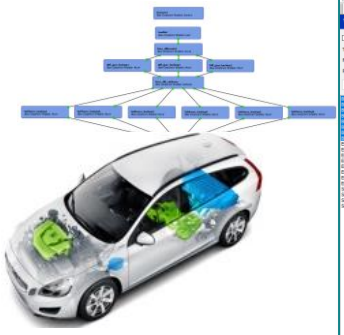
Define the vehicle architecture

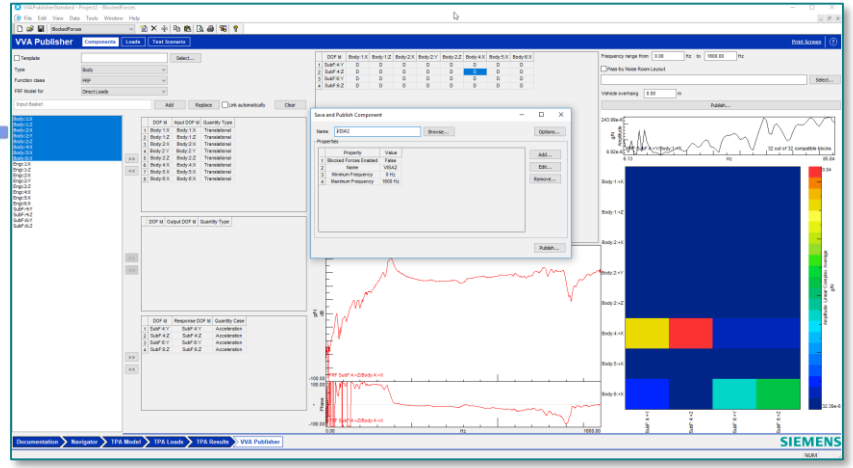
Create Validated Components

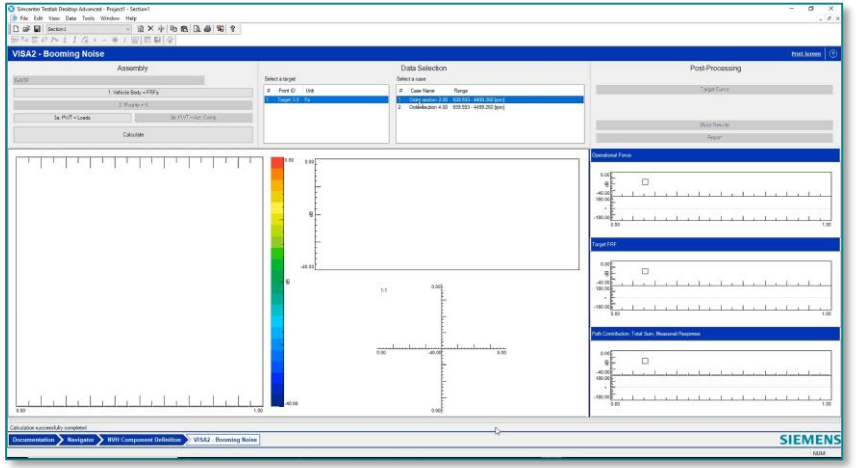
Populate Assemblies / Configurations

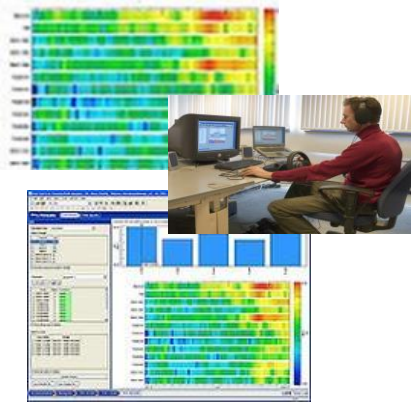
Perform Calculation

Contribution Analysis & Audio Replay & Reporting









Supported by Model (Lifecycle) Data Management

How can Simcenter help you ?
Implementation roadmap for component-based TPA

SIEMENS
Ingenuity for life

Technology transfer

End-to-end test system

Combining test and simulation

1 Engineering and Consulting

- Worldwide technology deployment & technology transfer services
- Dedicated approach for each application

2 Testing Solutions

- Integrated solution for transfer path analysis with shakers, sensors, hardware and software
- The reference solution for airborne and structureborne source characterization, substructuring and NVH Synthesis.
- Embedded in test-based NVH engineering solution covering TPA, structural dynamics, acoustics and rotating machinery

3 Simcenter Solution

- Single source provider for test and simulation models that can be used in a NVH Synthesis context
- Process implementation to predict NVH performance during the entire development process – concept, detailed engineering, full-vehicle

Thank you