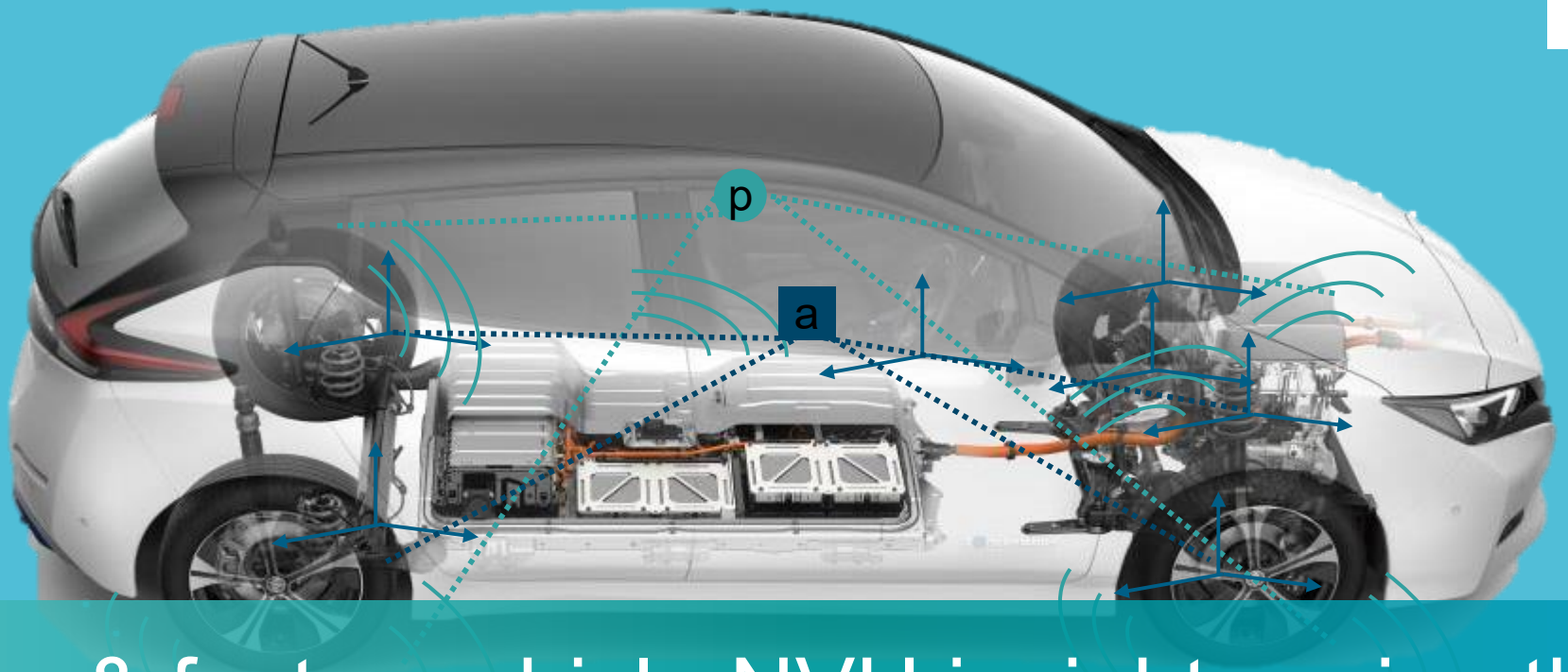
SIEMENS
Ingenuity for life



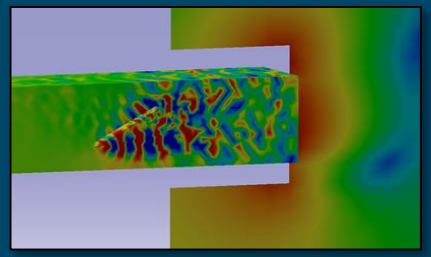
Better & faster vehicle NVH insights using the latest transfer path analysis methods

Webinar 20 November 2018

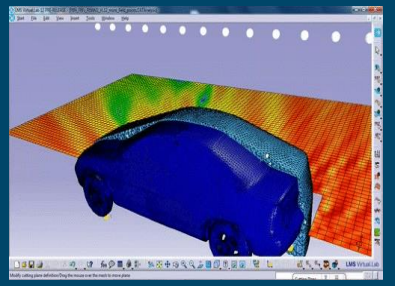
NVH Engineering Challenges

SIEMENS
Ingenuity for life

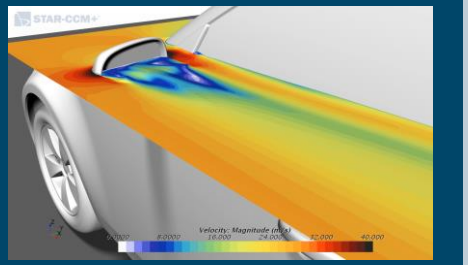
HVAC



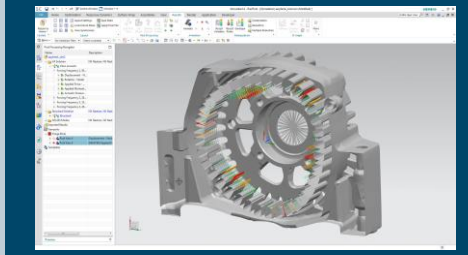
Pass-by noise



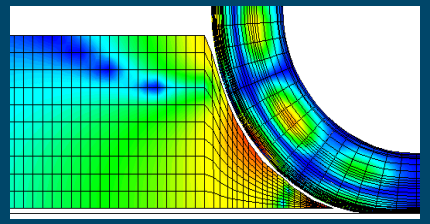
Wind noise



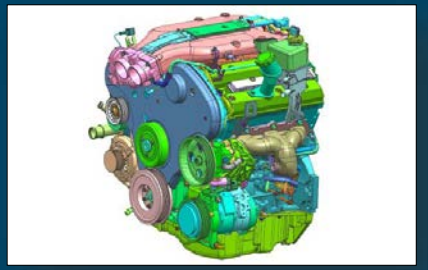
Electric motor



Road Noise



Engine



Better & faster vehicle NVH insights using the latest transfer path analysis methods

SIEMENS
Ingenuity for life

Introduction to transfer path analysis

Traditional TPA methods

Time-domain TPA

Component-based TPA

Model-based TPA

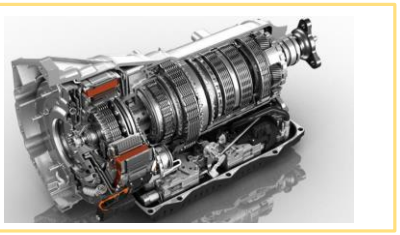
Conclusions

Introduction to Transfer Path Analysis

Source-transfer-receiver approach

SIEMENS
Ingenuity for life

Transmission



Drive line

HVAC

Exhaust

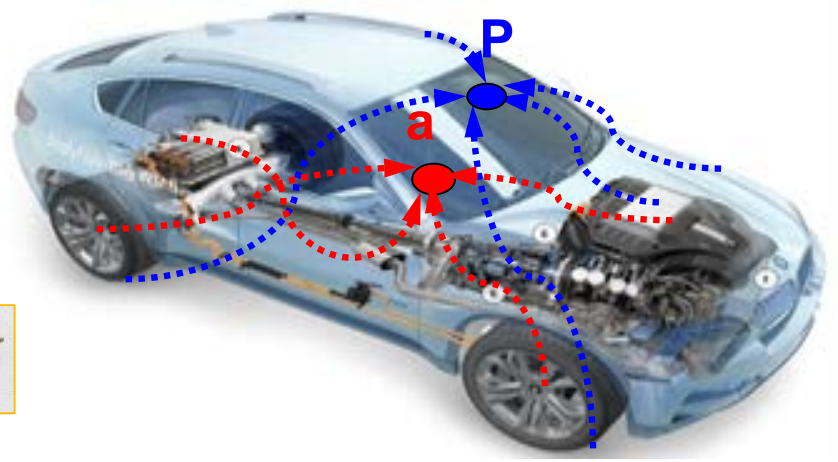
Wiper System

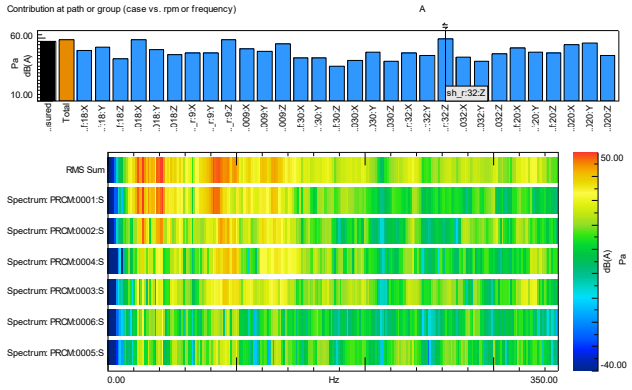
EPS

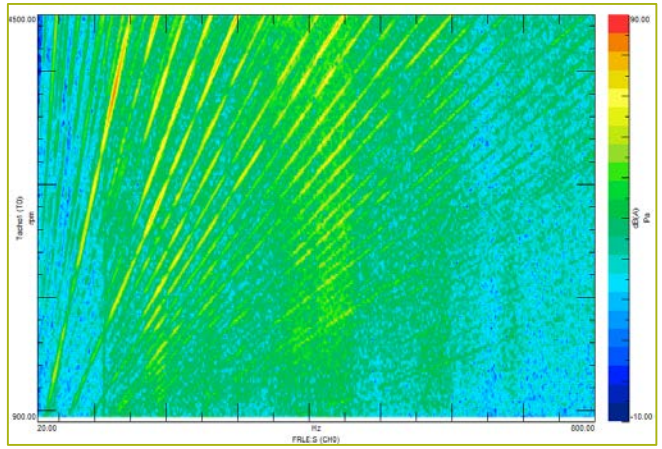
Tyres

Engine

(H)EV





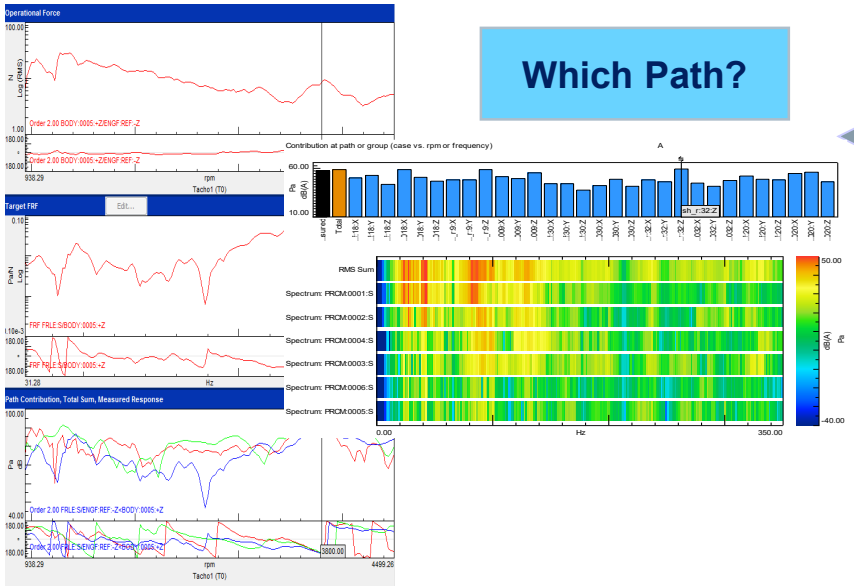


Source (F_i,Q_j) — X — Transfer (NTF) — = → Receiver (y_k)

Introduction to Transfer Path Analysis
TPA as part of Contribution Analysis

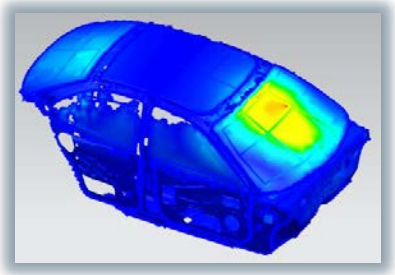
SIEMENS
Ingenuity for life

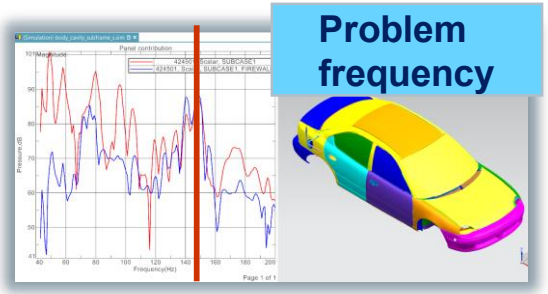
Different ways of looking at a NVH problem



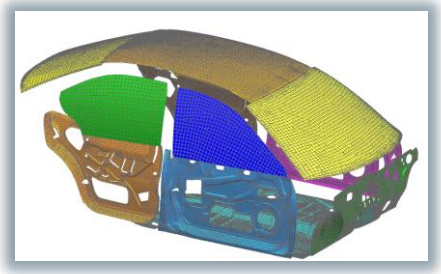
Which Path?

Which grid?

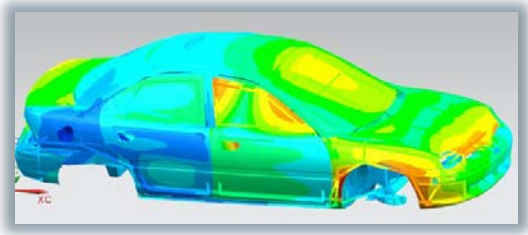




Problem frequency



Which Panel?



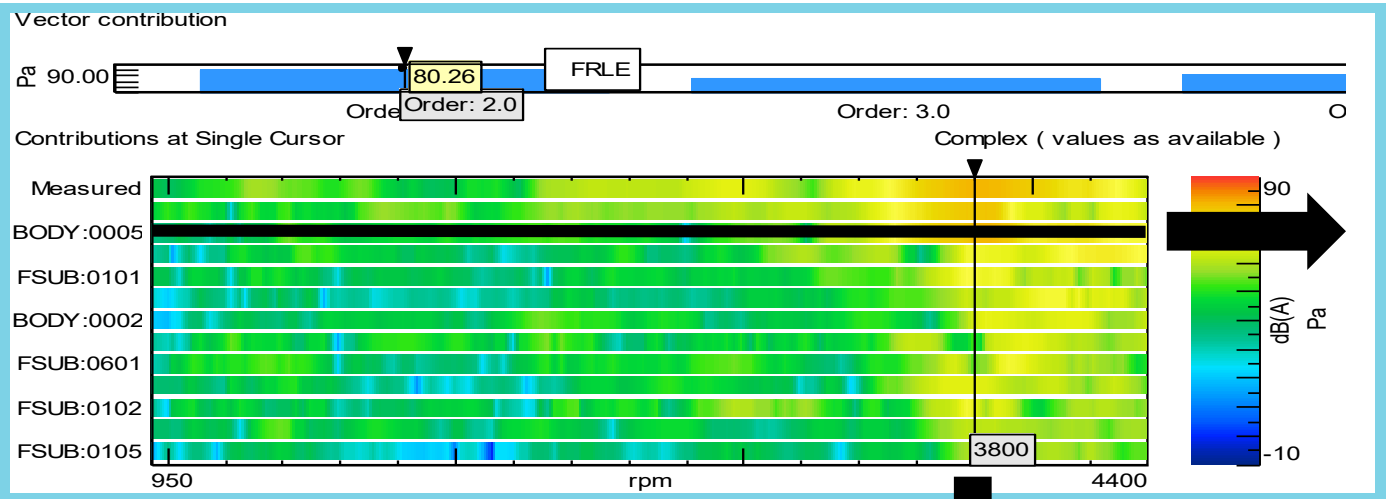
What operating shape?

Introduction to Transfer Path Analysis
TPA as part of Contribution Analysis

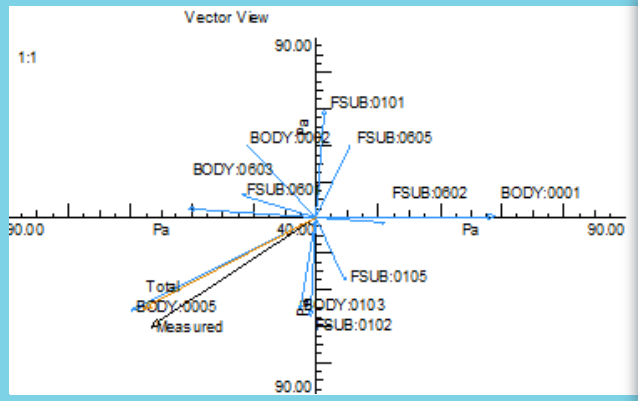
SIEMENS
Ingenuity for life

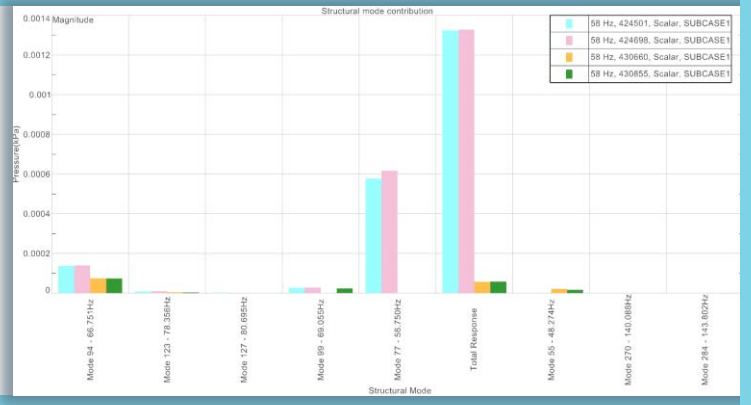
Step 1: Contribution Analysis

Paths



Frequency

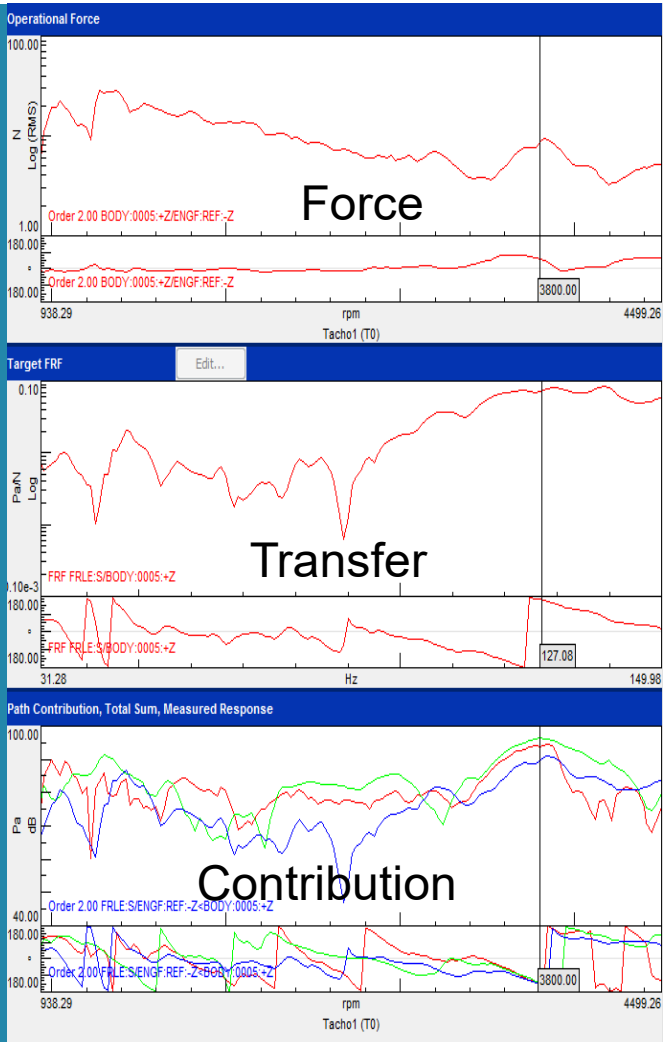




Amplitude Phase

Modal

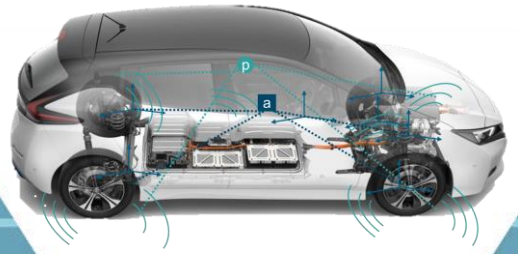
Step 2: Path Source Transfer



Transfer Path Analysis
Throughout the vehicle development cycle

SIEMENS
Ingenuity for life

Target Setting | **Concept validation** | **Detailed Engineering** | **Validation/Refinement**



Bench marking & Target setting

Concept Analysis

Load Identification

CAE based contribution analysis

What-if games & optimization

Troubleshooting

Critical component & Path Identification

Auralization & Optimization

Classical TPA | **Test/CAE combined TPA** | **Classical TPA**

Better & faster vehicle NVH insights using the latest transfer path analysis methods

SIEMENS
Ingenuity for life

Introduction to transfer path analysis

Traditional TPA methods

Time-domain TPA

Component-based TPA

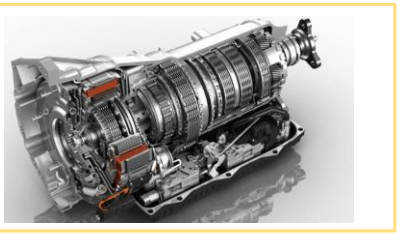
Model-based TPA

Conclusions

Transfer Path Analysis
Source-transfer-receiver approach

SIEMENS
Ingenuity for life

Transmission



Drive line

HVAC

Exhaust

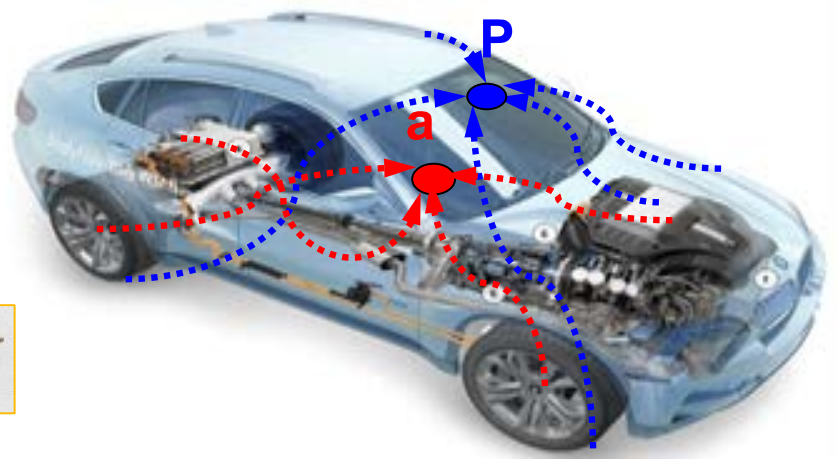
Wiper System

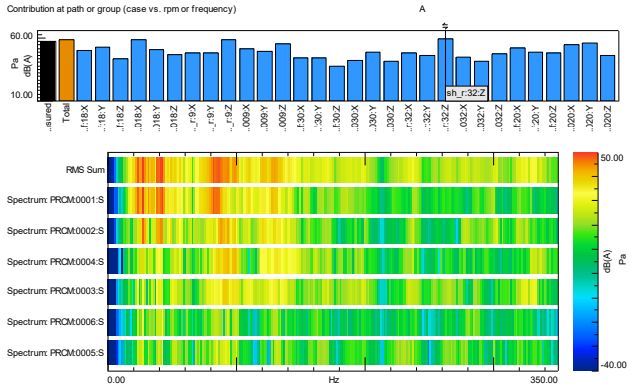
EPS

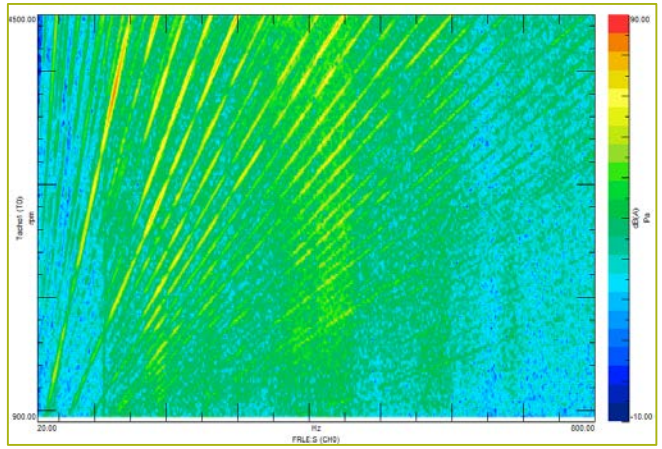
Tyres

Engine

(H)EV



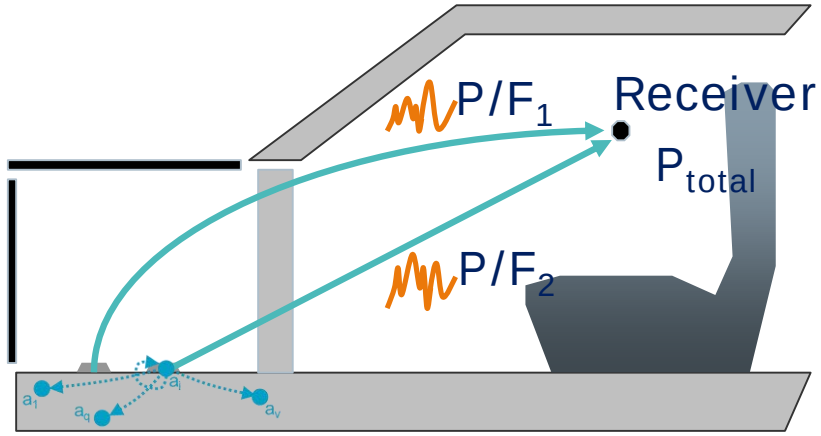




Source (F_i,Q_j) — X — Transfer (NTF) — = → Receiver (y_k)

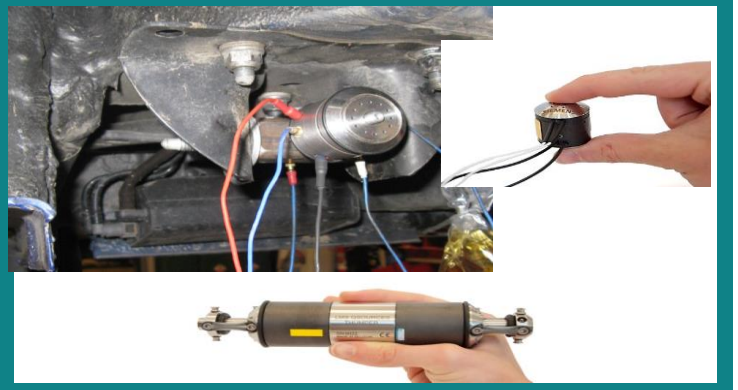
Traditional TPA methods
Efficient & Accurate FRF Acquisition

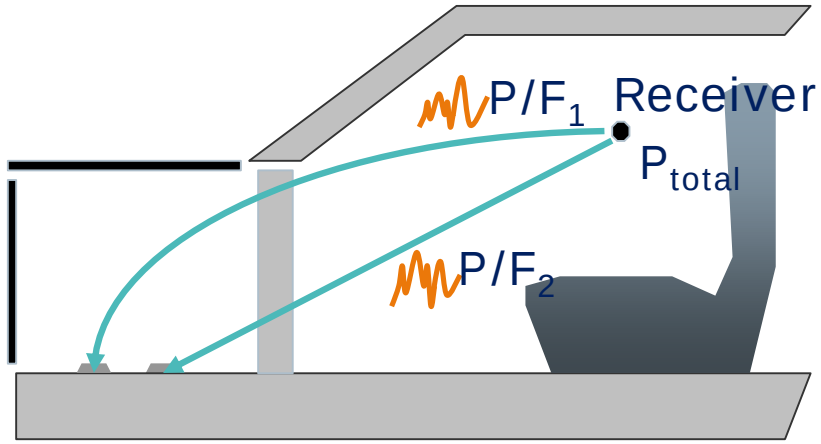
SIEMENS
Ingenuity for life



Direct FRF Measurements

- Modal Hammer
  - ✓ Common approach but prone to measurement and repeatability error
- Shaker
  - ✓ Miniaturized shakers can overcome many hammer issues





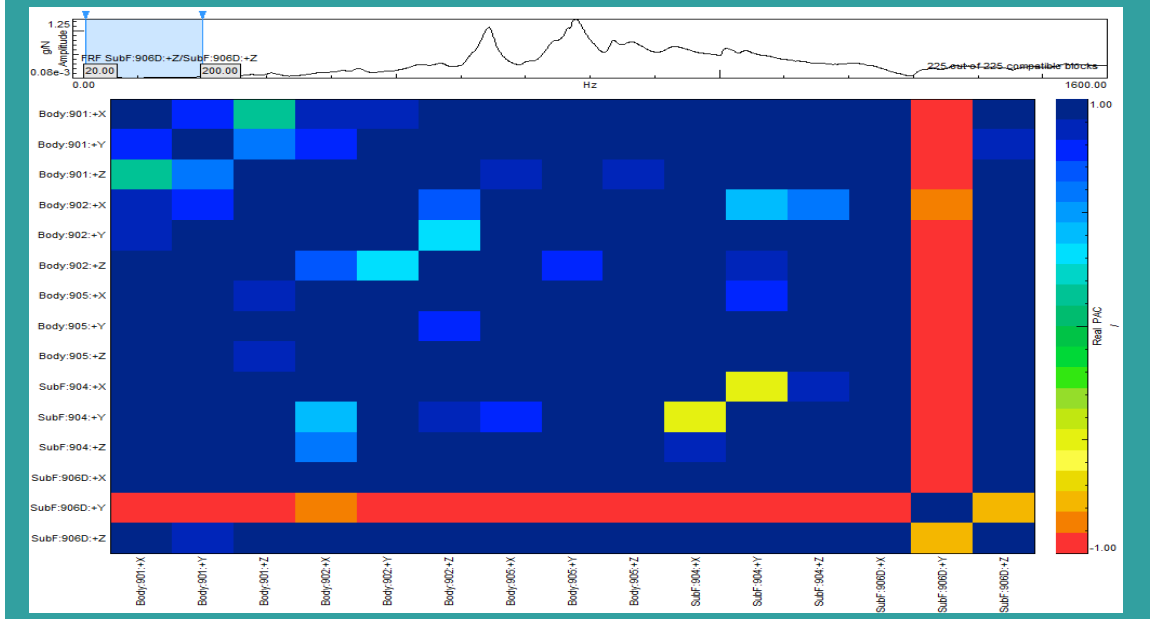
Reciprocal FRF measurement

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

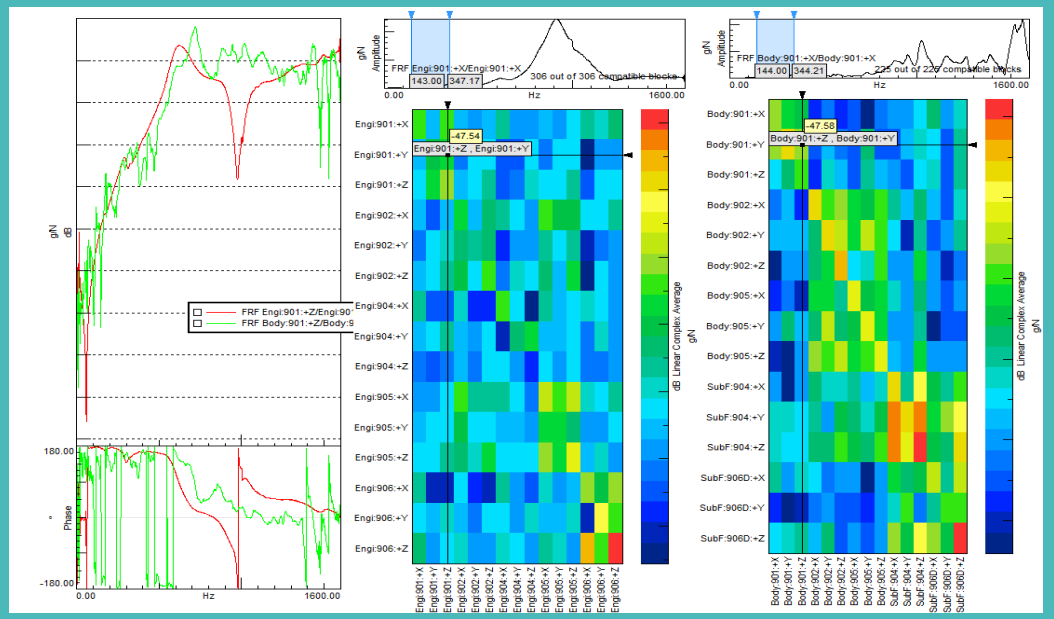
Traditional TPA methods

Requirements: Verify quality data quality and gain insight

SIEMENS
Ingenuity for life



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



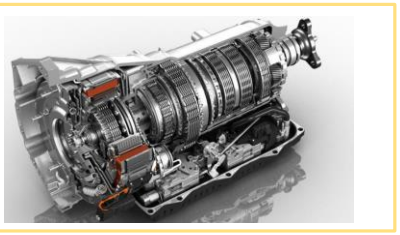
Gain insight in the system dynamics

1000+ FRFs in one view

Transfer Path Analysis
Source-transfer-receiver approach

SIEMENS
Ingenuity for life

Transmission



Drive line

HVAC

Exhaust

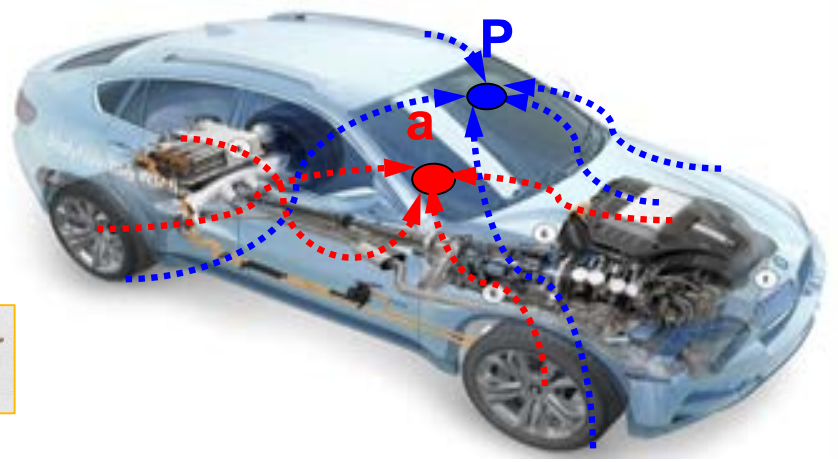
Wiper System

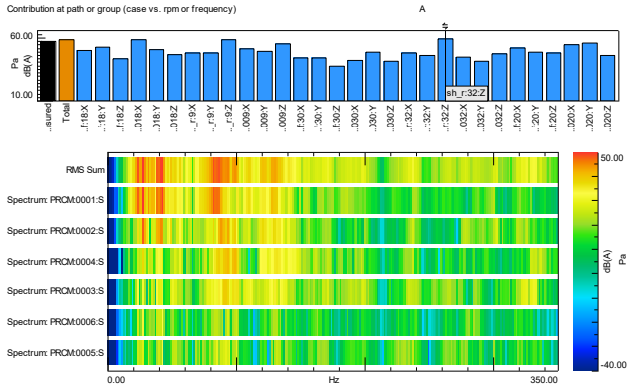
EPS

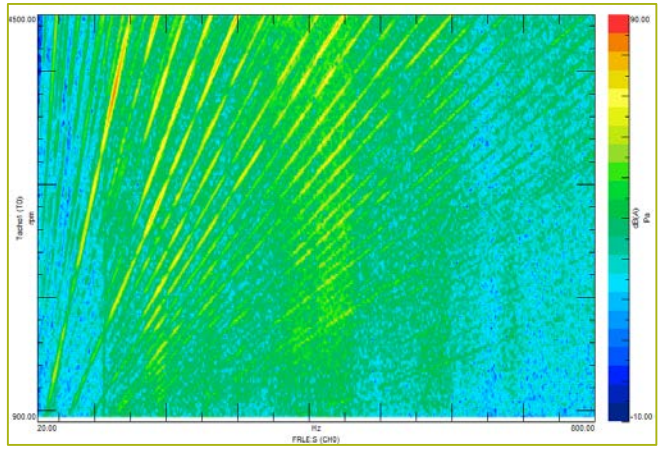
Tyres

Engine

(H)EV







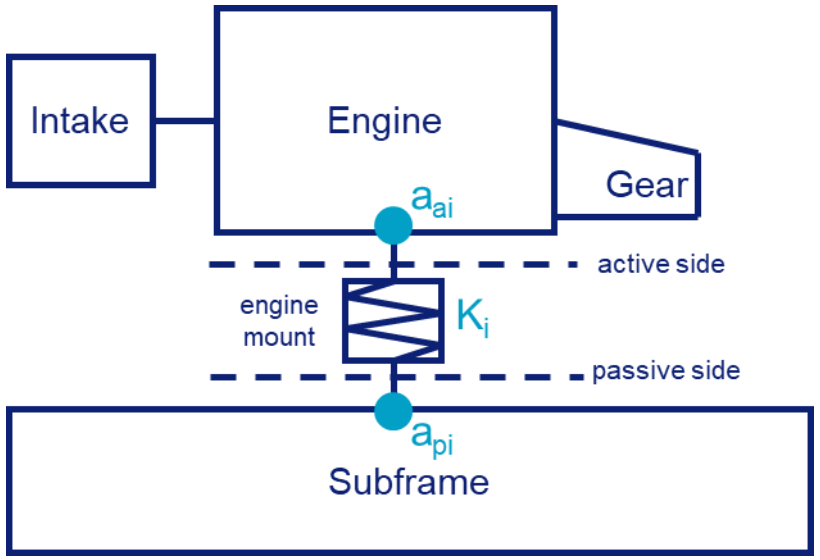
Source (F_i,Q_j) X Transfer (NTF) = Receiver (y_k)

Load identification methods
Mount stiffness and Matrix inversion

SIEMENS
Ingenuity for life

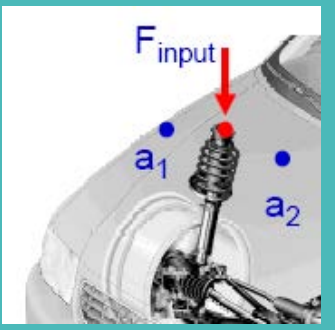
Mount Stiffness

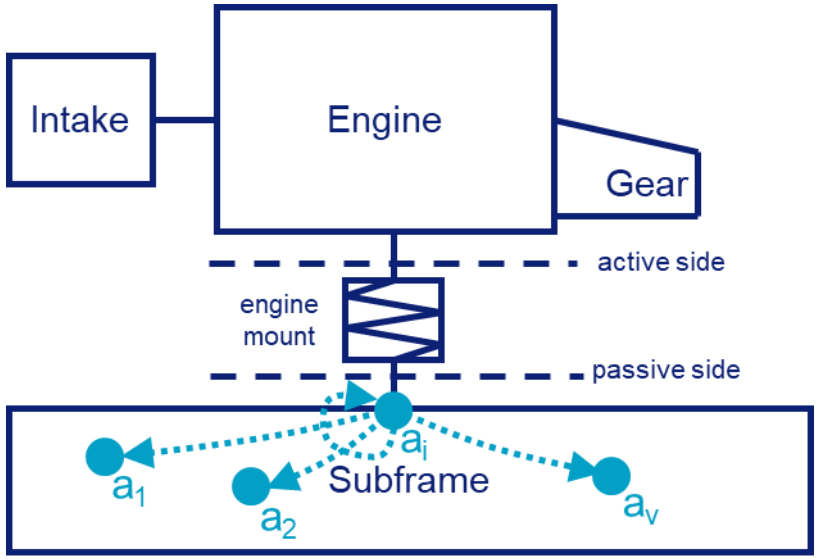
$$F_i(\omega) = K_i(\omega) \cdot \frac{(a_{ai}(\omega) - a_{pi}(\omega))}{-\omega^2}$$



Matrix Inversion

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





Load identification methods
Mount stiffness and Matrix inversion

SIEMENS
Ingenuity for life

Mount Stiffness

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

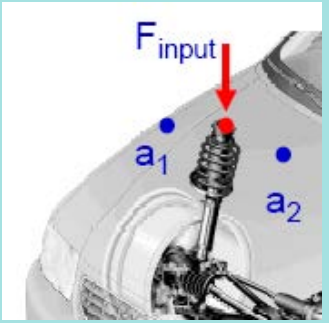
Requires
- FRFs to targets only
- Active & Passive side responses
- Mount Stiffness Curves
- Enough isolation over mount (~20dB)

(dis)advantages
- Only target-FRFs required
- Insight in mount-isolation performances

- Disassembly into trimmed-body condition
- Requires accurate mount-stiffness curves

Matrix Inversion

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



Requires
- FRFs to targets & indicators
- Full structural FRF matrix
- Only Passive side responses
- Enough over-determination (>2x)

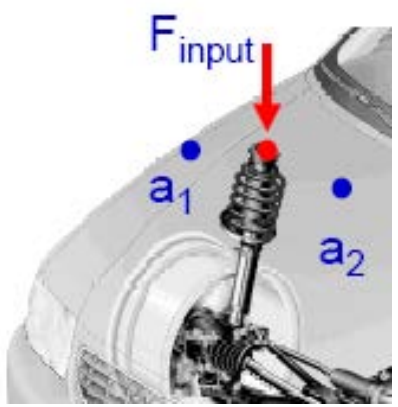
(dis)advantages
- No Mount-stiffness curves required
- Detailed body information

- Disassembly into trimmed-body condition
- Time-consuming FRF measurement (Full Matrix)
- No separation of nearby paths

Traditional TPA method: Advanced load identification

Strain sensors: separating nearby paths

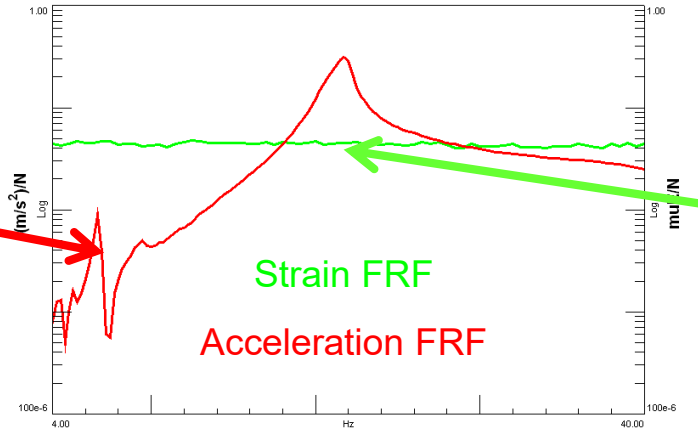
SIEMENS
Ingenuity for life

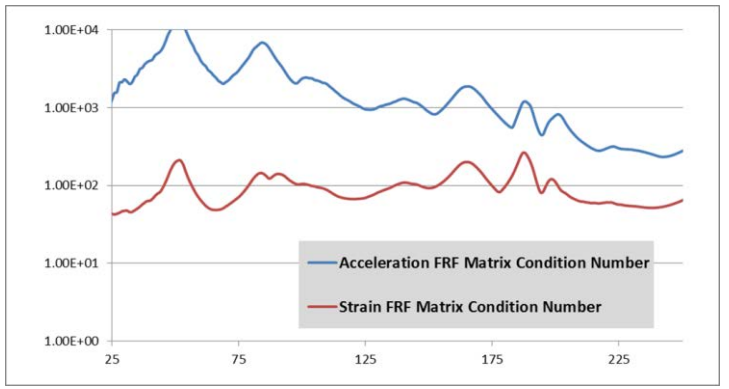


$$\{F(\omega)\} = [H(\omega)]^{-1} \cdot \{a(\omega)\}$$

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

Load identification
Simcenter Testlab OPAX

SIEMENS
Ingenuity for life

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

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

Fast method applying force estimation method using parametric model to reduce required measurements

Requires
- FRFs to targets (structural FRFs are optional)
- Active & Passive side responses
- Acceleration (or Strain) indicators

(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)

Better & faster vehicle NVH insights using the latest transfer path analysis methods

SIEMENS
Ingenuity for life

Introduction to transfer path analysis

Traditional TPA methods

Time-domain TPA

Component-based TPA

Model-based TPA

Conclusions

Frequency-domain vs. Time-domain TPA

SIEMENS
Ingenuity for life

Frequency-domain TPA

- ➔ Order analysis
- ➔ Spectrum analysis

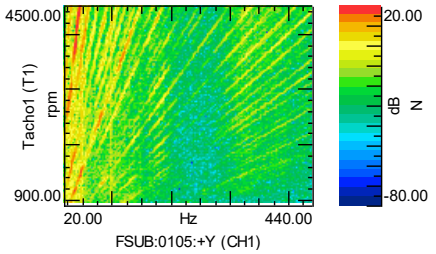
- ✓ Run-up & run-down
- ✓ Stationary: e.g road noise

Time-domain TPA

- ➔ Time traces

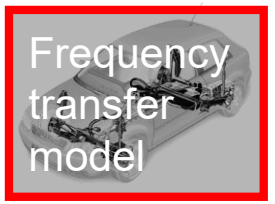
- ✓ Run-up & run-down
- ✓ Stationary: e.g road noise
- ✓ Transient: e.g. engine start-up
- ✓ Semi-stationary: e.g. idle noise, frequency modulation …

Loads (orders, spectra)



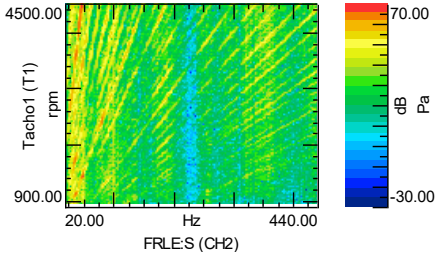
X

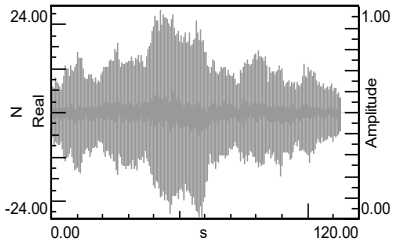
NTF



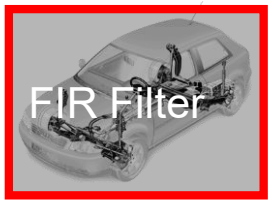
=

Path contributions (orders, spectra)

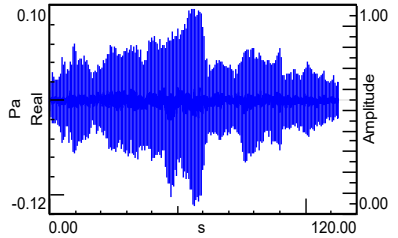




⊗



=



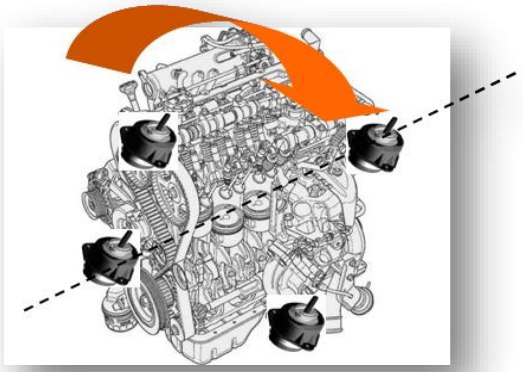
Loads (time traces)

Path contributions (time traces)

Auralization, Signature Analysis, Sound Quality metrics ...

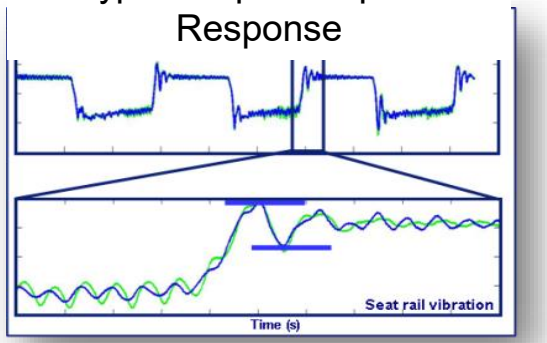
Time-domain TPA for Tip-in/Tip-out
Application Example

SIEMENS
Ingenuity for life



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

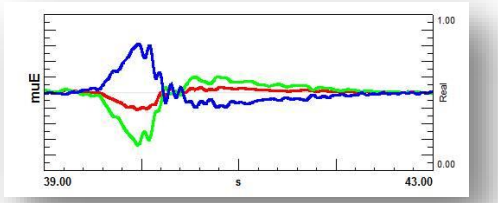
Typical Tip-in / Tip-out Response



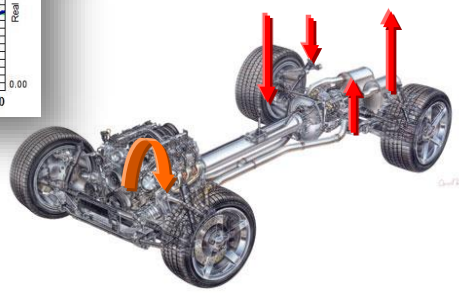
Transient Load identification
Strain gage technology
Low frequency

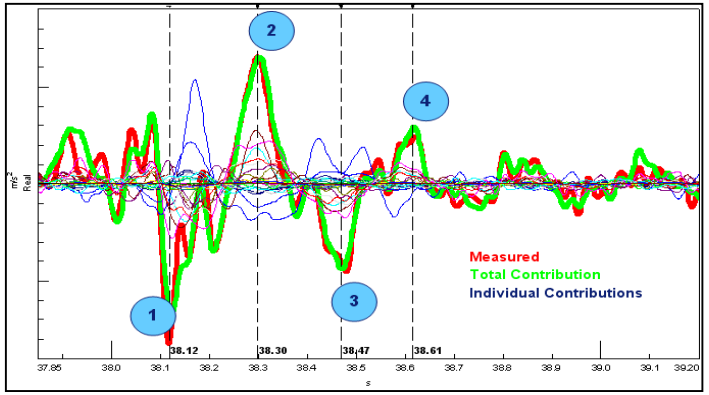
…in "full NVH Context"
To link transient loads
to Dynamic Interface Forces…

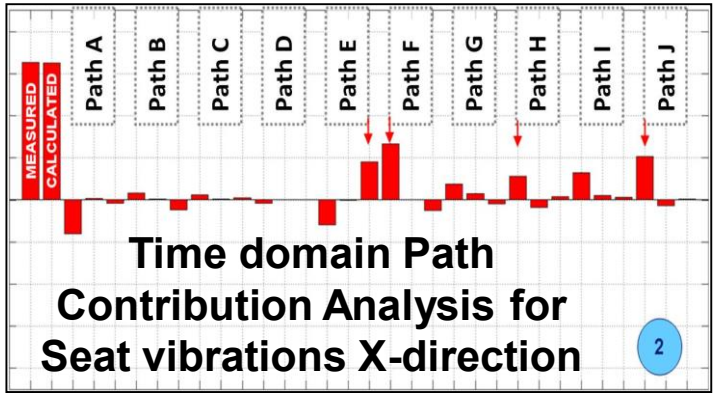
…Transfer Path Analysis (TPA)
Insights in contribution
to NVH Comfort



Strain responses
(right) during Tip-in







MITSUBISHI

Time-domain Transfer Path Analysis for Transient Phenomena Applied to Tip-in/Tip-out (Shock & Jerk)
H. Shiozaki, Y.Iwanaga, MMC, T. Geluk ,F. Daenen, J, Van Herbruggen, LMS, SAE 2012-01-1545

Better & faster vehicle NVH insights using the latest transfer path analysis methods

SIEMENS
Ingenuity for life

Introduction to transfer path analysis

Traditional TPA methods

Time-domain TPA

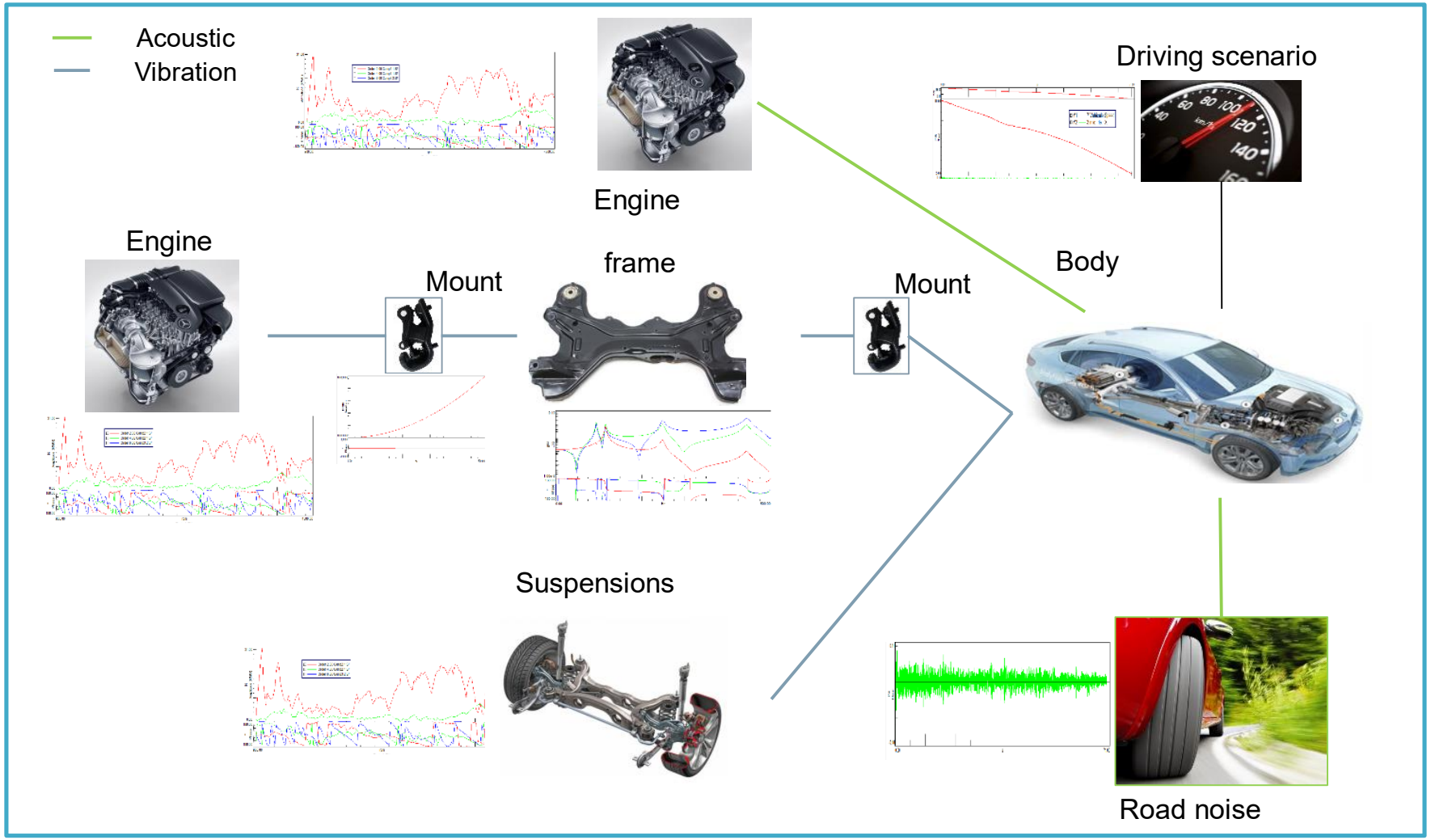
Component-based TPA

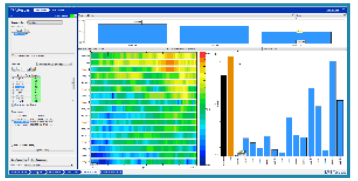
Model-based TPA

Conclusions

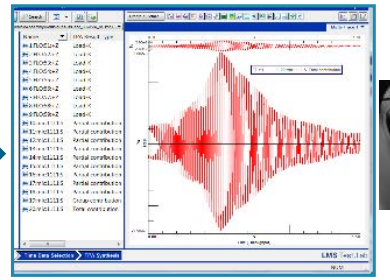
Component-based TPA
Concept

SIEMENS
Ingenuity for life

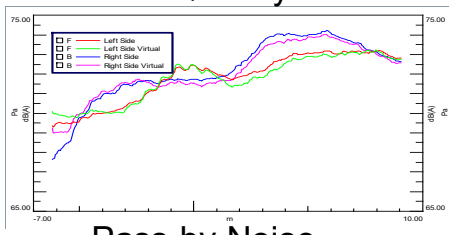




Compare Contribution Analysis



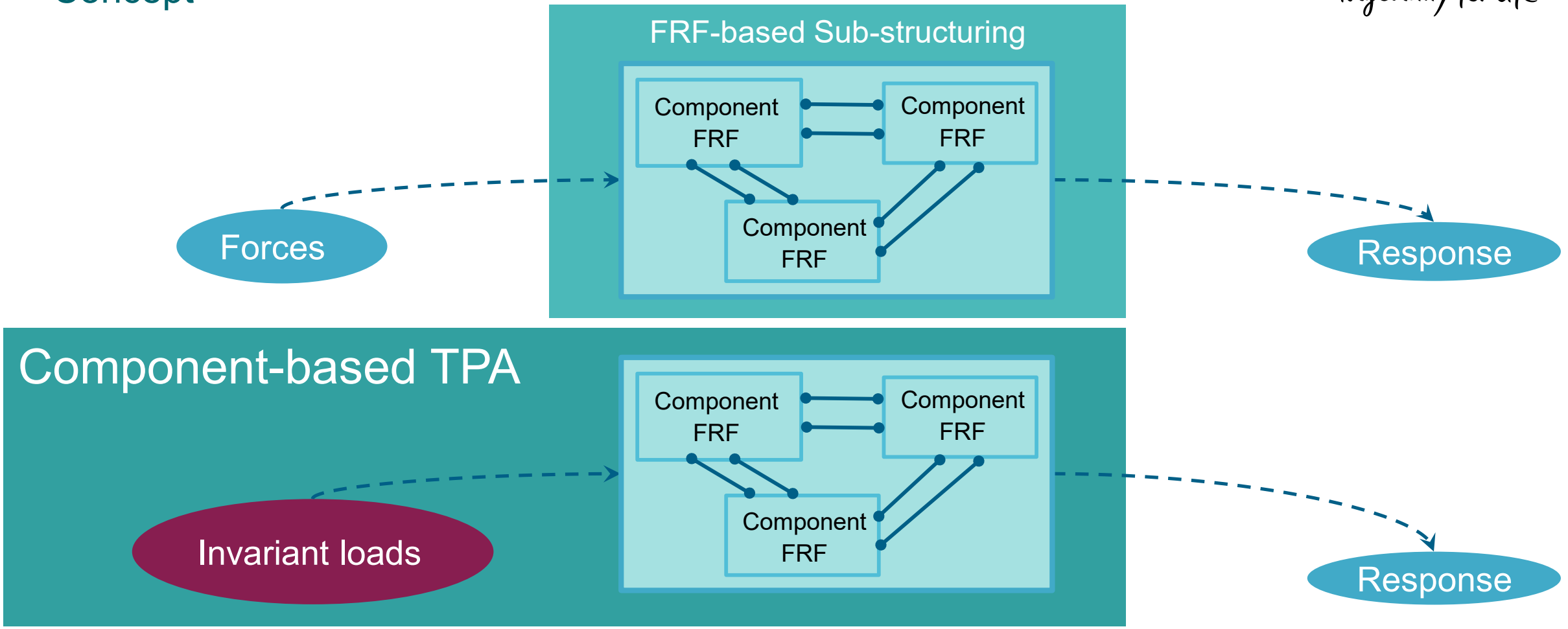
Sound Synthesis Result SQ Analysis



Pass-by Noise Synthesis

Component-based TPA
Concept

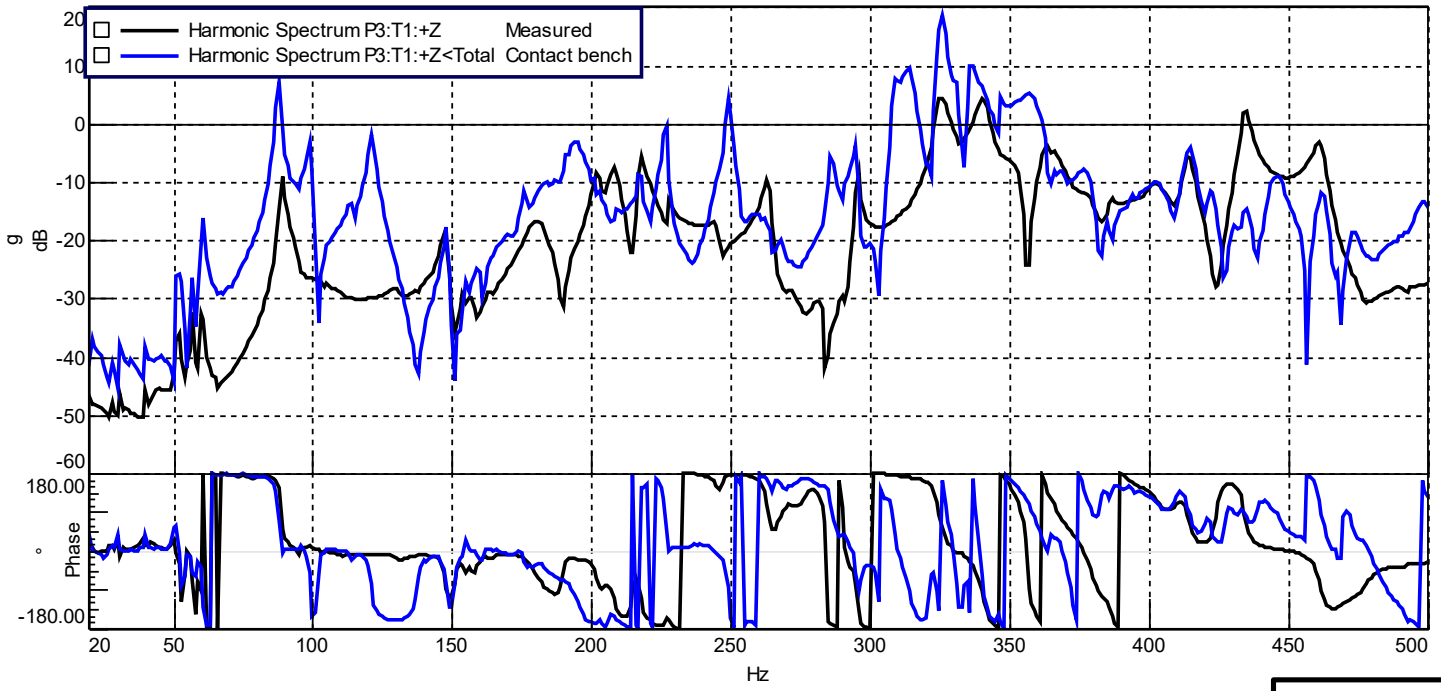
SIEMENS
Ingenuity for life



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

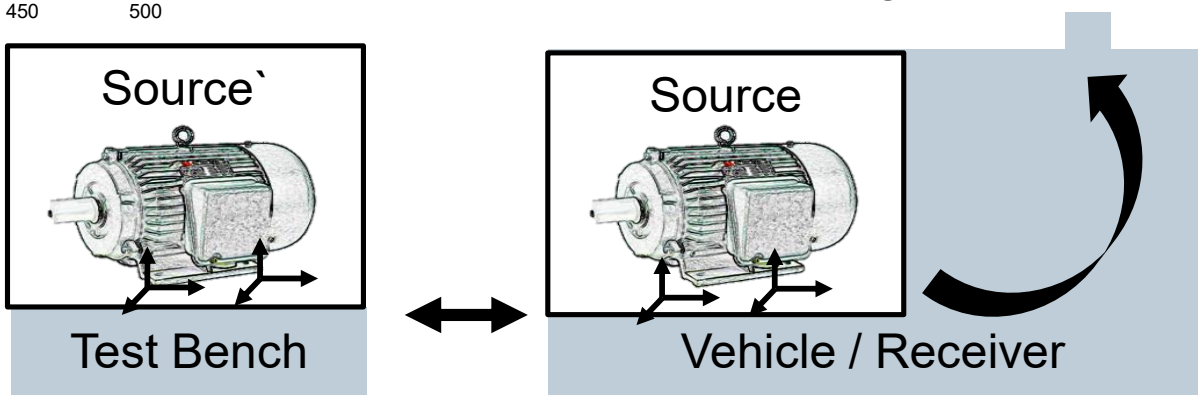
Example: Source-Receiver interaction
Strong coupling case – Structure Borne

SIEMENS
Ingenuity for life



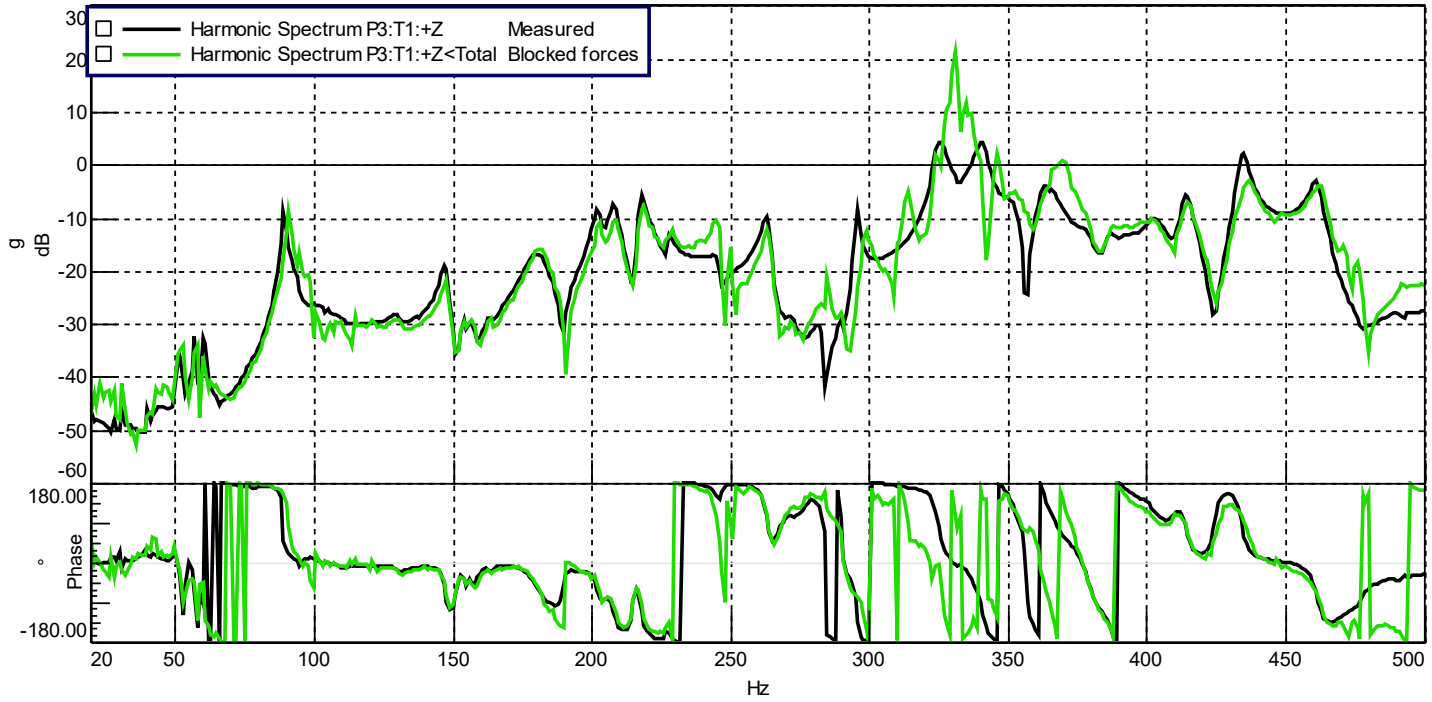
~~Exchange Contact Forces~~

Predict Target Response



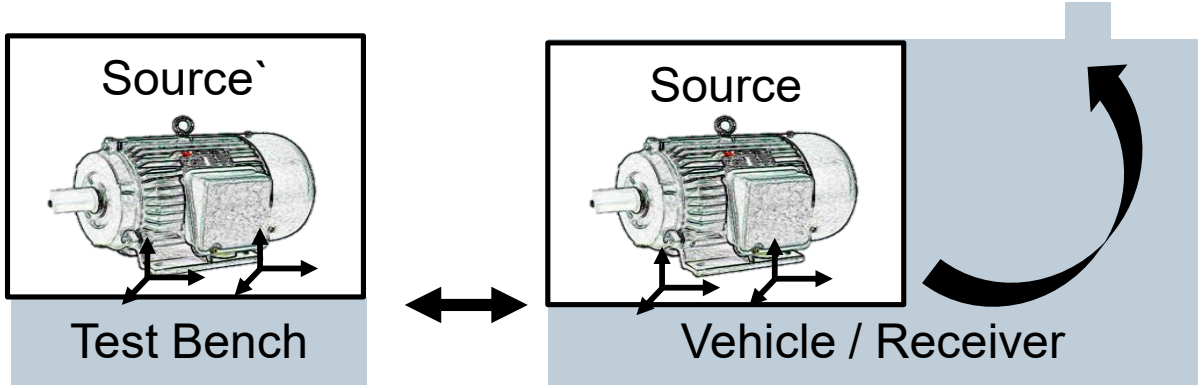
Example: Source-Receiver interaction
Strong coupling case – Structure Borne

SIEMENS
Ingenuity for life



Exchange Blocked Force
Invariant Source Description

Predict Target Response

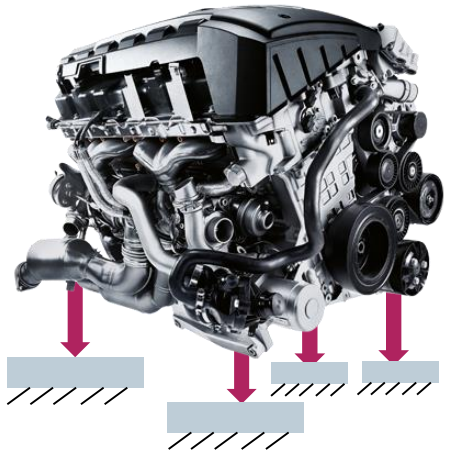


Component-based TPA
Invariant load characterization

SIEMENS
Ingenuity for life

Structure-borne:

Blocked Forces



Airborne:

Volume Velocities

Invariant load characterization

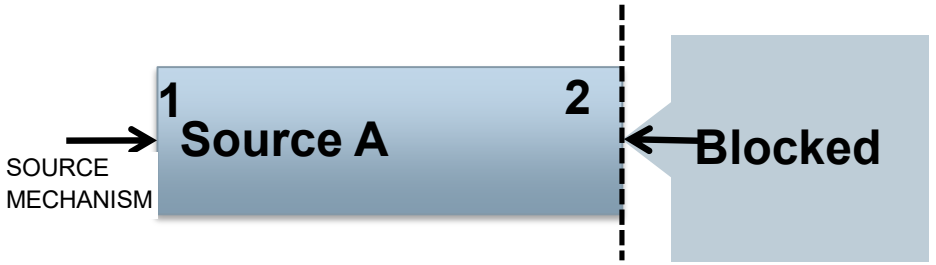
Receiver independent, allowing:

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

Component-based approach
Structure-borne: Blocked Forces

SIEMENS
Ingenuity for life

1. Blocked Force



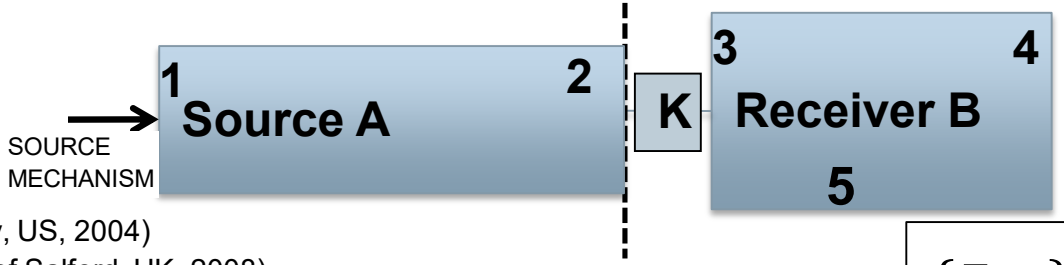
$\{F_{2Bl}\}$

2. Free Velocity

$\{A_{2Free}\}$

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

3. In-Situ TPA



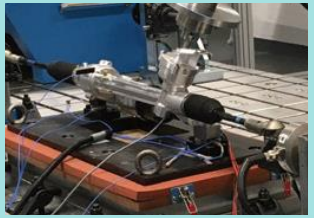
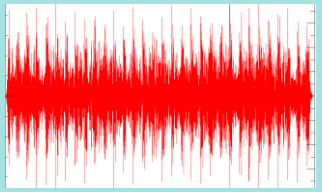
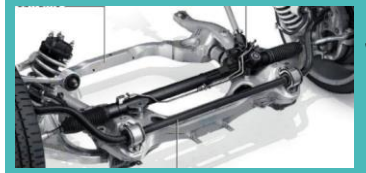
$$\{F_{2Bl}\} = [H_{52}^{AB}]^{-1}\{A_5\}$$

Calculate Interface Force using FBS

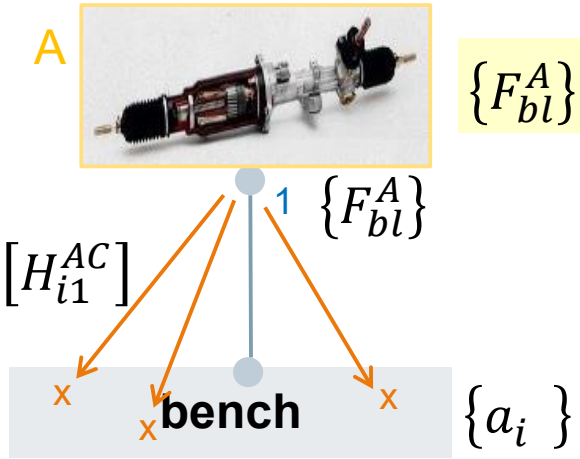
(Park / Gu, Ford Motor Company, US, 2004)
(Moorhouse & Elliott, University of Salford, UK, 2008)

Component-based TPA
Application example of a steering system

SIEMENS
Ingenuity for life

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

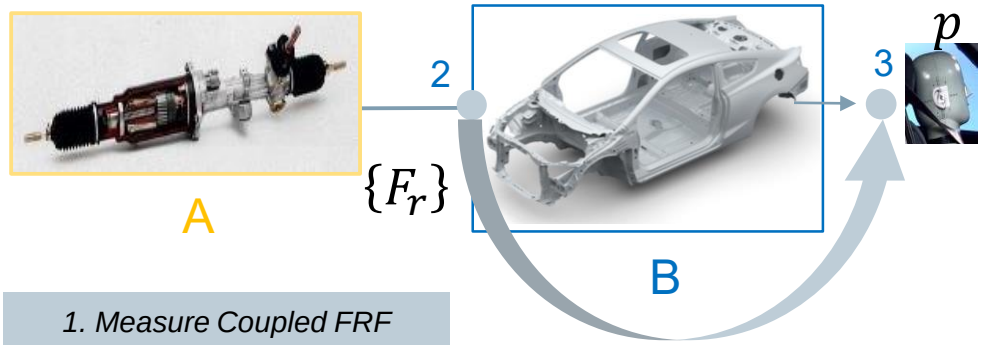
Invariant Source Load (TEST)



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

$\{a_i\}$

Full System Transfer Function

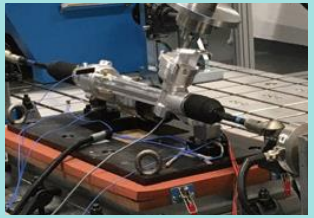
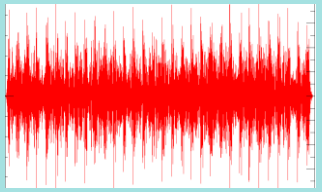
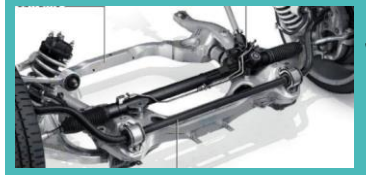


1. Measure Coupled FRF

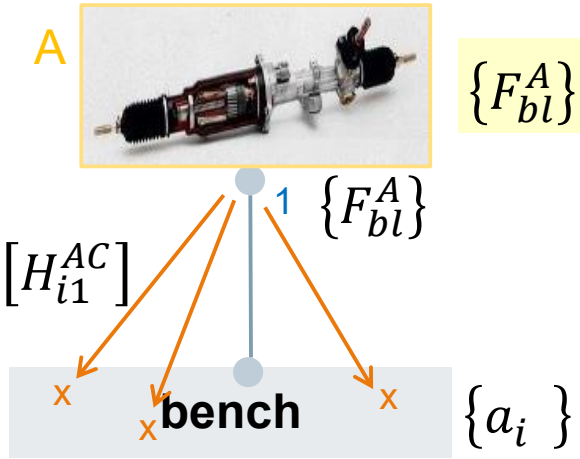
$$p = [H_{32}^{AB}] * \{F_{bl}^A\}$$

Component-based TPA
Application example of a steering system

SIEMENS
Ingenuity for life

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)

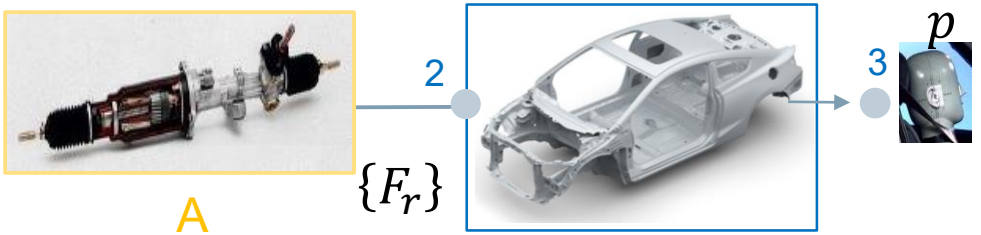


$$\{F_{bl}^A\} = [H_{i1}^{AC}]^{-1} * \{a_i\}$$

$\{a_i\}$

Full System Transfer Function

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



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

Application example of predicting Air-borne pass-by noise performance

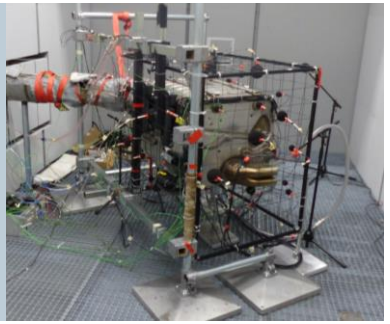
SIEMENS
Ingenuity for life

Invariant description of sources

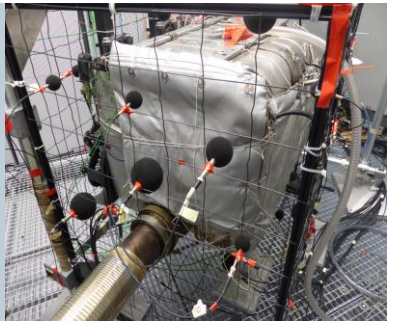
Recombine with selected components to synthesize SYSTEMS

Predict NVH performance

VARIANT A

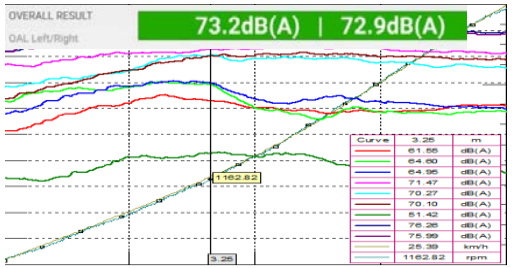


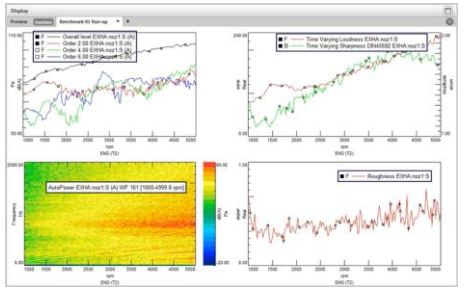
VARIANT B



VEHICLE 1

VEHICLE VARIANTS



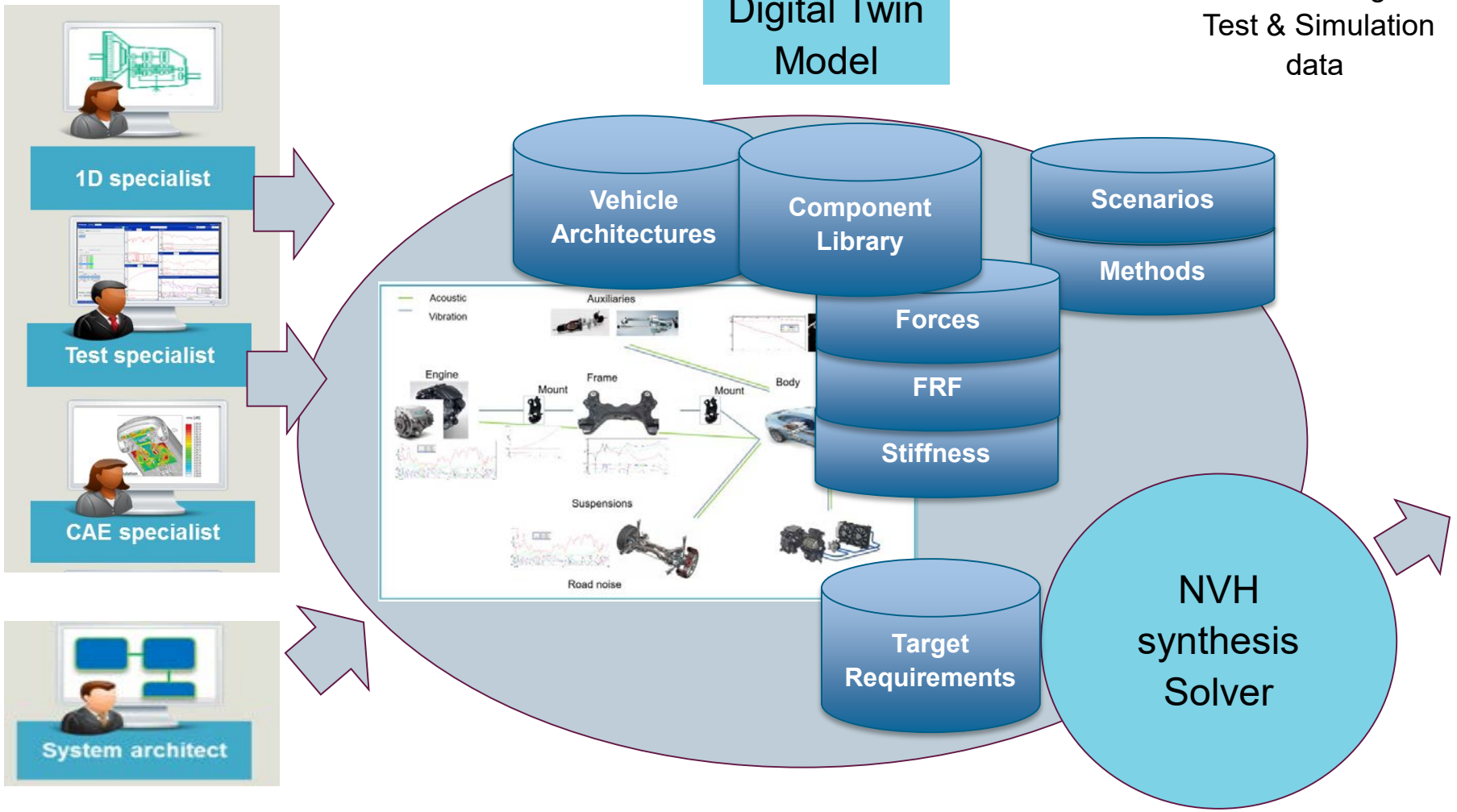


All Design Variants

Vehicle Variants

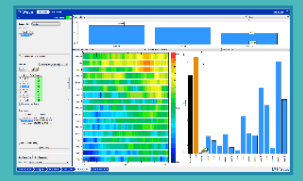
Component-based TPA
System Engineering for NVH

SIEMENS
Ingenuity for life

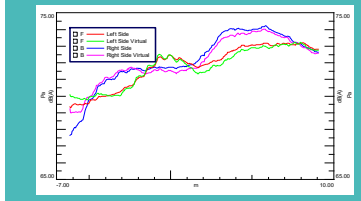


Combining Test & Simulation data

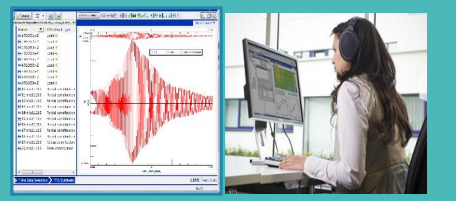
Compare Contribution Analysis



Pass-by Noise Synthesis



Sound Synthesis Result



NVH Driving Simulator Evaluation

Better & faster vehicle NVH insights using the latest transfer path analysis methods

SIEMENS
Ingenuity for life

Introduction to transfer path analysis

Traditional TPA methods

Time-domain TPA

Component-based TPA

Model-based TPA

Conclusions

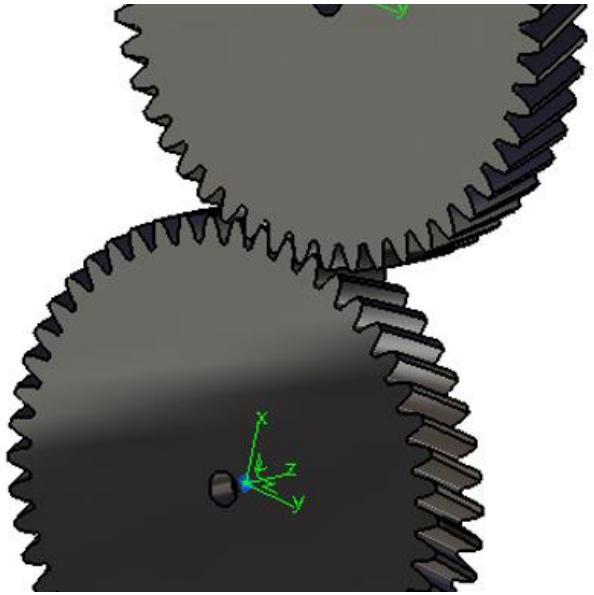
Model-base TPA

Gearbox Noise – Multi-Body Dynamics + Structural Dynamics

SIEMENS
Ingenuity for life

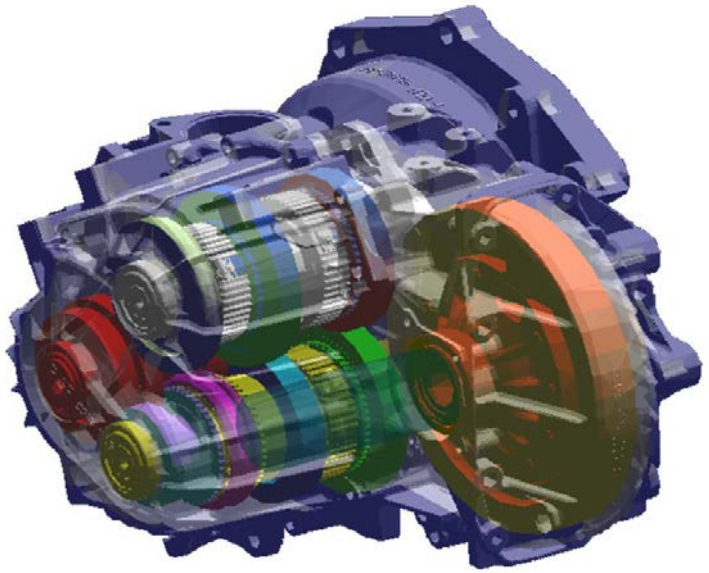
SOURCE

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



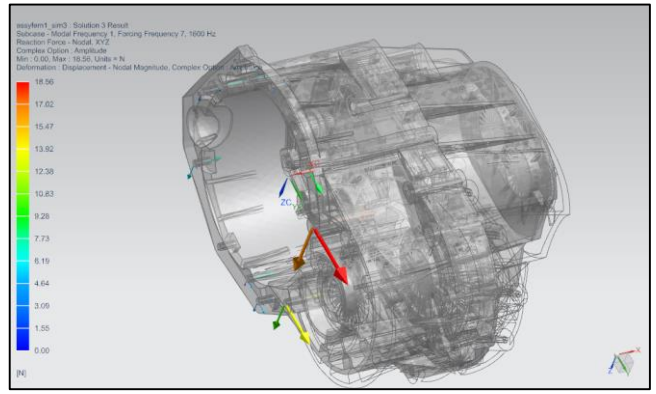
PATH TRANSFER

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

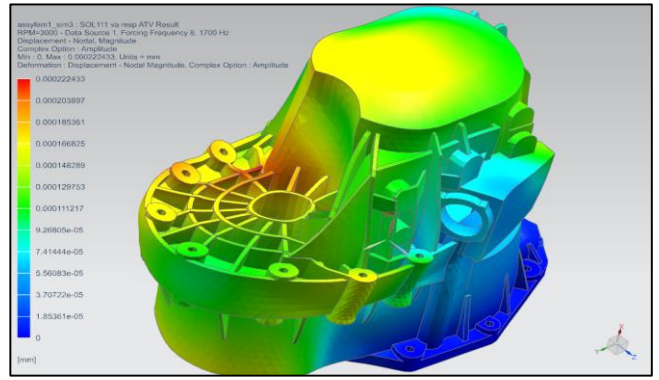


RECEIVER

Operational connection forces (to body)



Operational surface vibrations

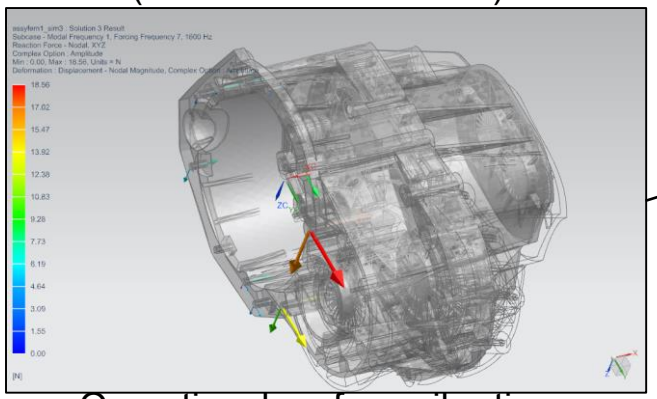


Gearbox Noise – Structural Dynamics and Acoustics

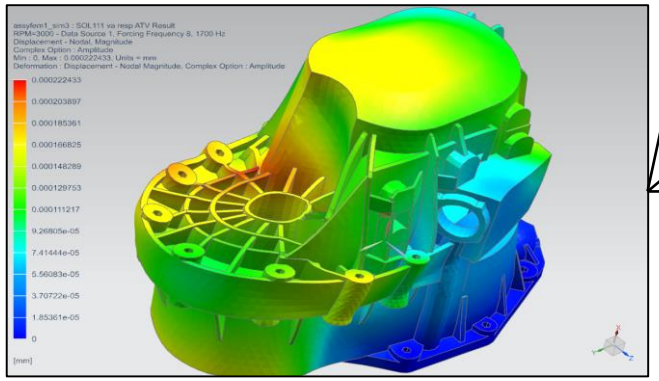
SIEMENS
Ingenuity for life

SOURCE

(structure borne noise)

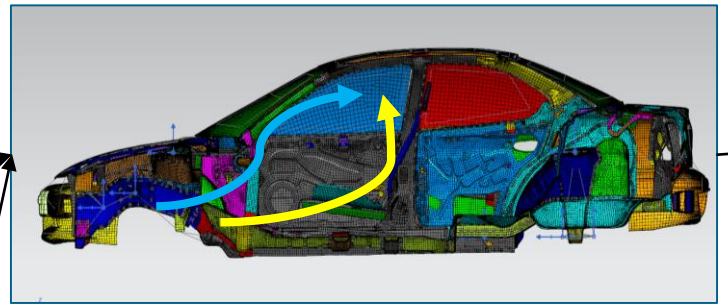


Operational surface vibrations
(Airborne noise)

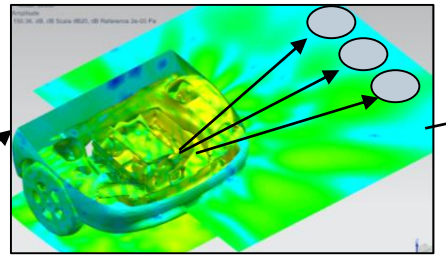


PATH TRANSFER

Vibro-Acoustic FRFs

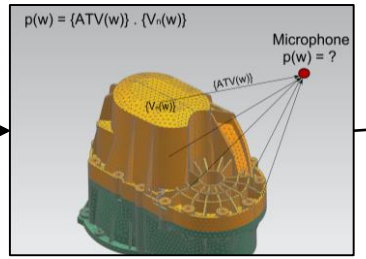


Acoustic FRFs SPL/ surface vibration



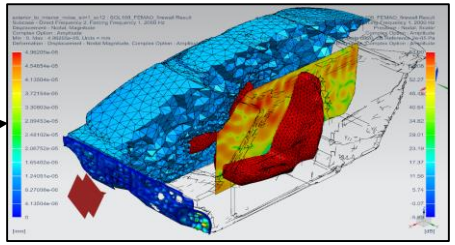
Installed condition

Free radiation condition

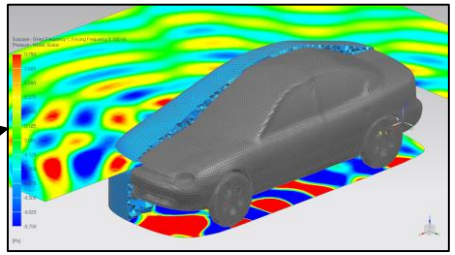


RECEIVER

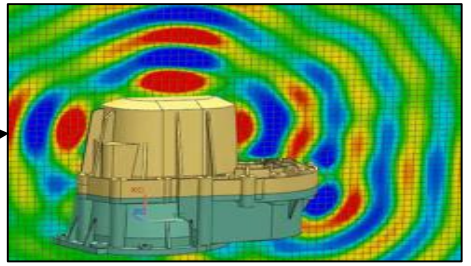
Cabin Powertrain Noise



Exterior Pass-By Noise



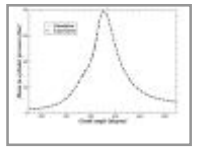
Ext. Component Noise



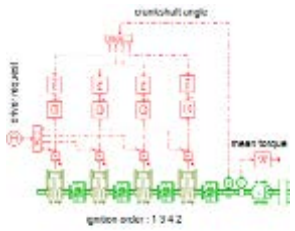
Model-based TPA
Application example: Low frequency driveline booming

SIEMENS
Ingenuity for life

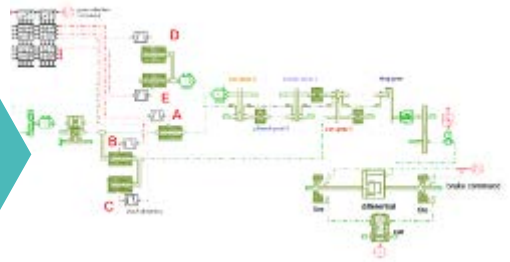
Extending TPA to system simulation and controls development



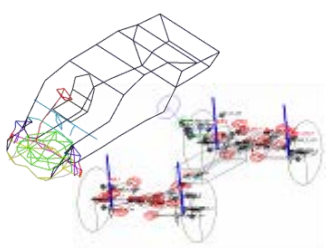
Combustion Pressure



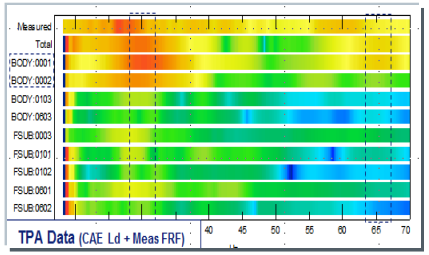
Engine Model



Transmission Model

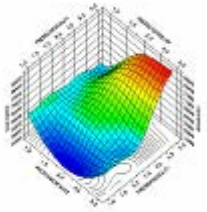


Driveline + Chassis & Vehicle



Vibro-acoustic response

TPA Analysis



ECU / TCU

Clutch + Transmission + Torque Converter

Driveline properties Geometric & mount design

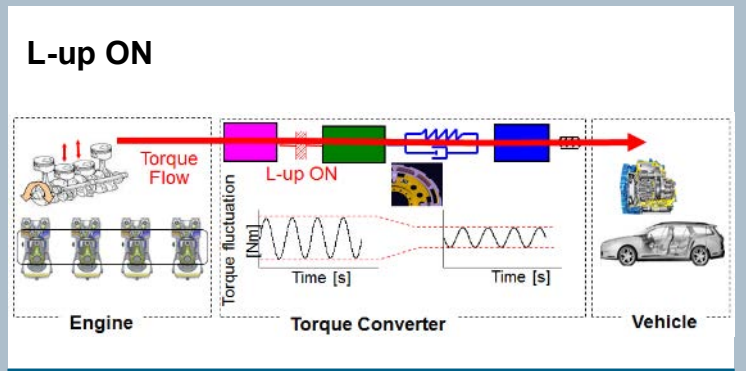
Controls development — Traditional NVH Engineering

Aisin AW
Strengthens its position as technology partner

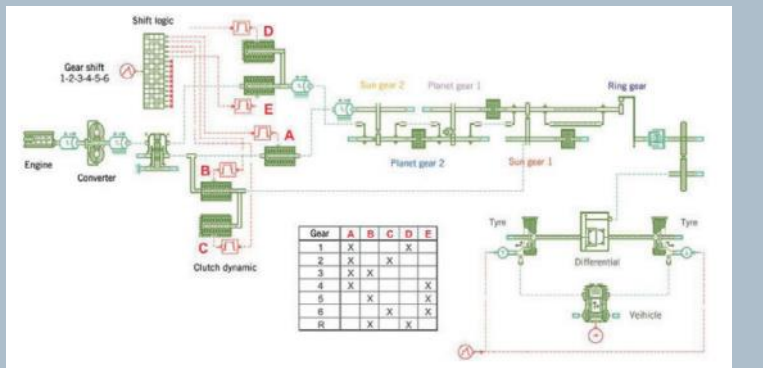
SIEMENS
Ingenuity for life

- **Gained 50 percent time reduction when troubleshooting a new NVH issue**
- **Significantly reduced overall development time**
- **Recognized as technology partner of automotive OEMs, resulting in competitive advantage**

Reducing booming, judder and gear noise



Energy flow lock-up booming



Full-vehicle simulation

- Deploy a full vehicle model based approach for the prediction and elimination of clutch judder
- Employ full vehicle modeling approach combining test, 3D and 1D simulation methodologies

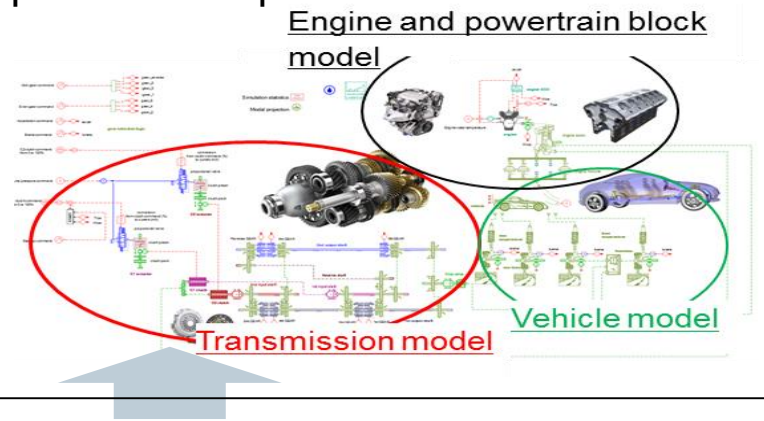
"Many NVH techniques we learned from Simcenter Engineering services are now part of our standard development process, such as transfer path analysis."

Hiroki Tsuji, Group Manager, Core Component Engineering Department

Aisin AW
Process deployment for lock-up booming investigation

SIEMENS
Ingenuity for life

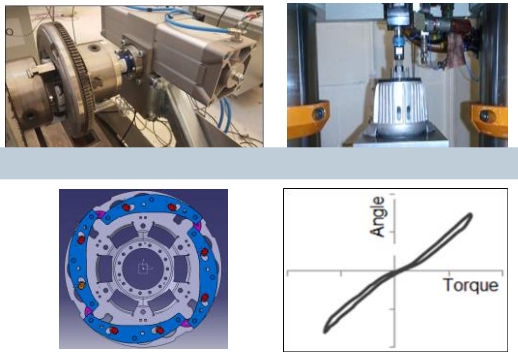
Torsional driveline model
Coupled with suspension and vehicle model



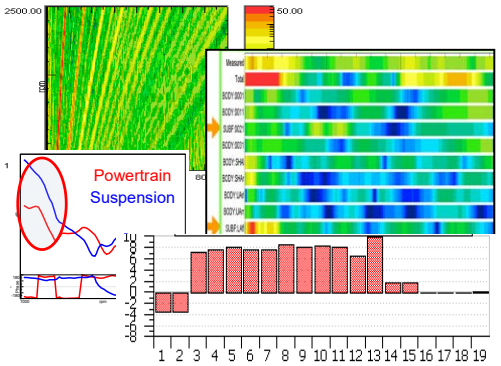
Update & Validate

Complement

Component – system tests
Vehicle tests



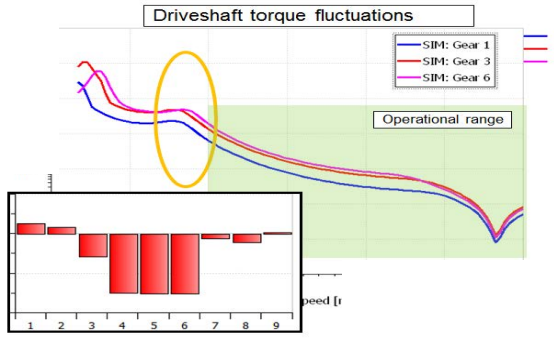
Diagnose
Insights



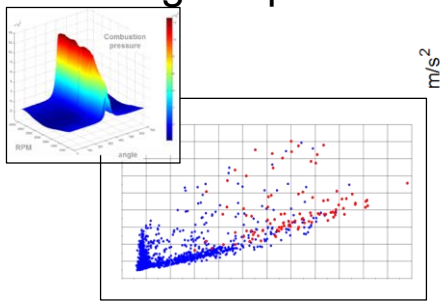
Scalable model complexity
f(accuracy, information)

	Engine	T/M	SUSPENSION	BODY
Master (not to be modeled)	HF engine	All internal details with clearances	3D full physical	FE
Level 1	MVEM	Simple ratio with equivalent inertia	1D	
Level 2	Mapped engine + 3D body	Simple ratio with equivalent inertia and clearance	2D	2D
Level 3	Cylinder pressure tables + 3D body	TM with distributed inertias and stiffness	2D with NVH tire model	2D + FRF

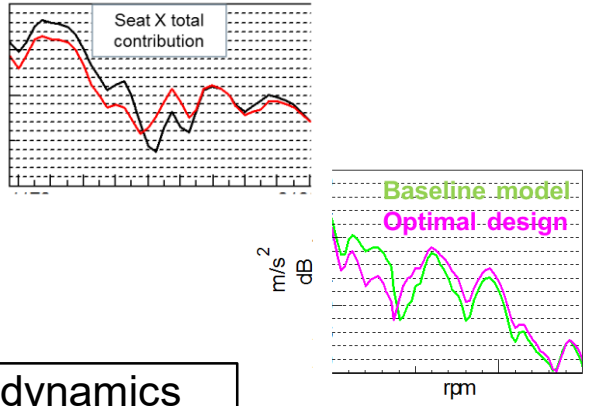
Sensitivity studies



Design exploration
Change impact



Modification studies



Model provides insight in rotational dynamics
& coupling driveline and suspension dynamics

Better & faster vehicle NVH insights using the latest transfer path analysis methods

SIEMENS
Ingenuity for life

Introduction to transfer path analysis

Traditional TPA methods

Time-domain TPA

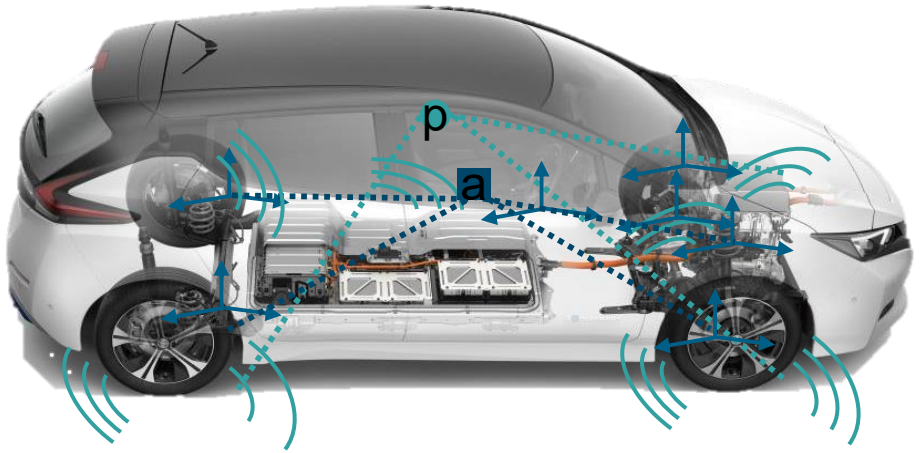
Component-based TPA

Model-based TPA

Conclusions

Transfer Path Analysis
Conclusion

SIEMENS
Ingenuity for life



Transfer Path Analysis (TPA) has been a key method in NVH Engineering for the past decades

Evolutions have kept TPA up-to-date:

- ✓ Faster TPA analyses with tools like OPAX
- ✓ Time-domain TPA to capture transients for eg. start/stop events
- ✓ Using 3D and 1D models to allow contribution analysis throughout development
- ✓ Component-based TPA to extend modular approaches from passive components to include the actual sources

Thank you! Want to know more?

SIEMENS
Ingenuity for life

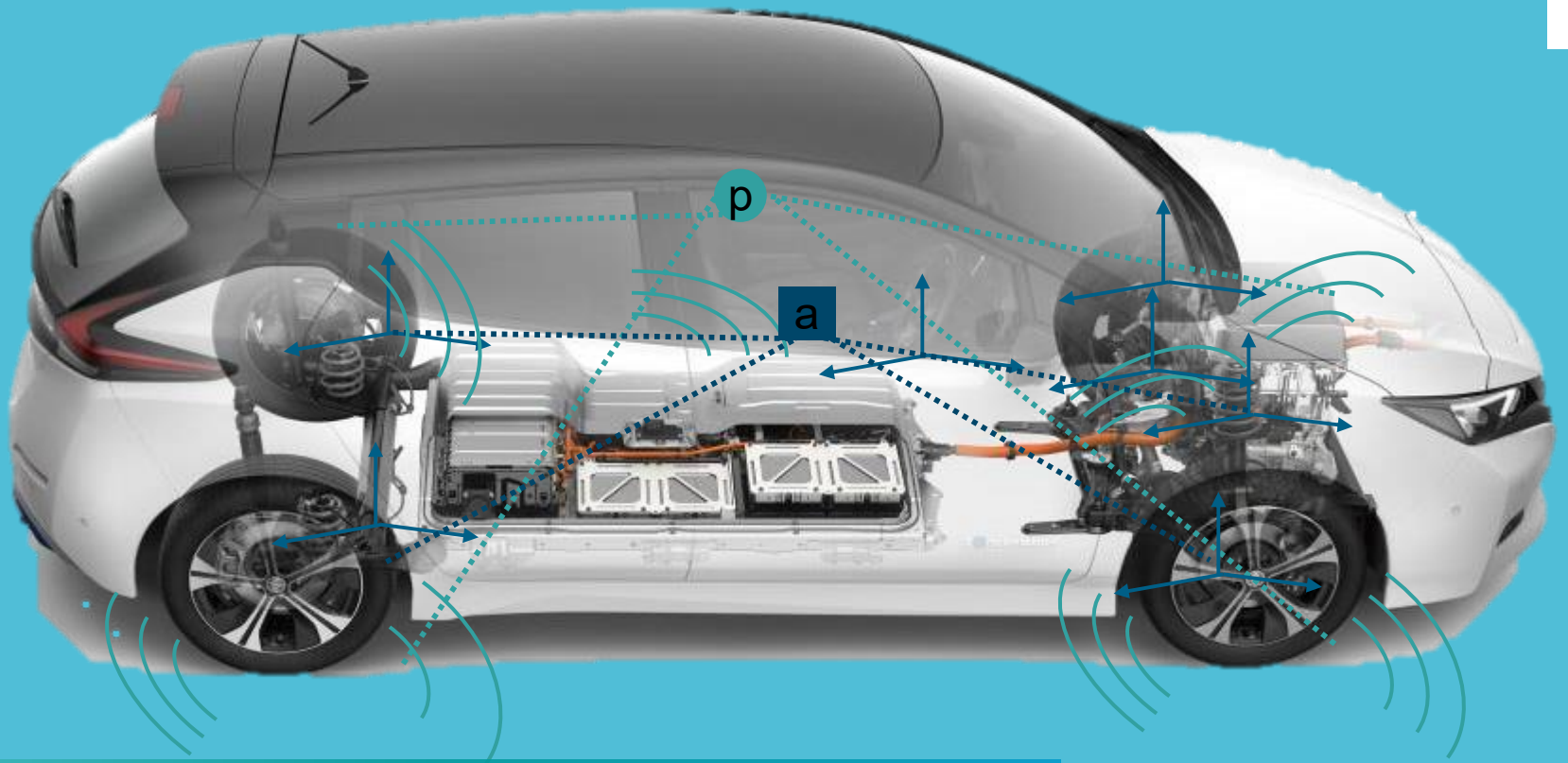
Read more

Explore, share and learn

Watch videos

Contact the expert

SIEMENS
Ingenuity for life



Thank you!

Join us – Simcenter Conference

SIEMENS
Ingenuity for life

Discover the **2018 Simcenter Conference,** an exciting event that brings together simulation, test and design exploration in an industry themed agenda that contains over 100 presentations from simulation & test experts.

Speakers

ABT
Access
ACT
ADG Mobility
Airbus
Aker Solutions
Apex Group
Atlanting
AVL Qpunkt
AZL
BAE Systems
BASF
B&B-AGEMA
BMW
Continental
Daimler
Danfoss
Dipolo
E-cooling
Faurecia Clean Mobility
FORD
Gustomsc
Honeywell
Hoval
Hyundai
Iceotope
IFP
Imamoter
InDesA
Irkut
Jaguar Landrover
JCB
JSC NPO Energomash
Mahle
Mitsubishi
NRG
Opel
Poclain Hydraulics
Qinetiq
Renault
Ricardo
Rolla SP Propellers
SACE
SAIC Motor
Skolkovo Institute
Stadler Rail
Tetrapack
Unilever
Valeo
VDL
Voith Turbo
Volvo Truck
Vyaire Medical
Wartsila
ZF
ZFW
…