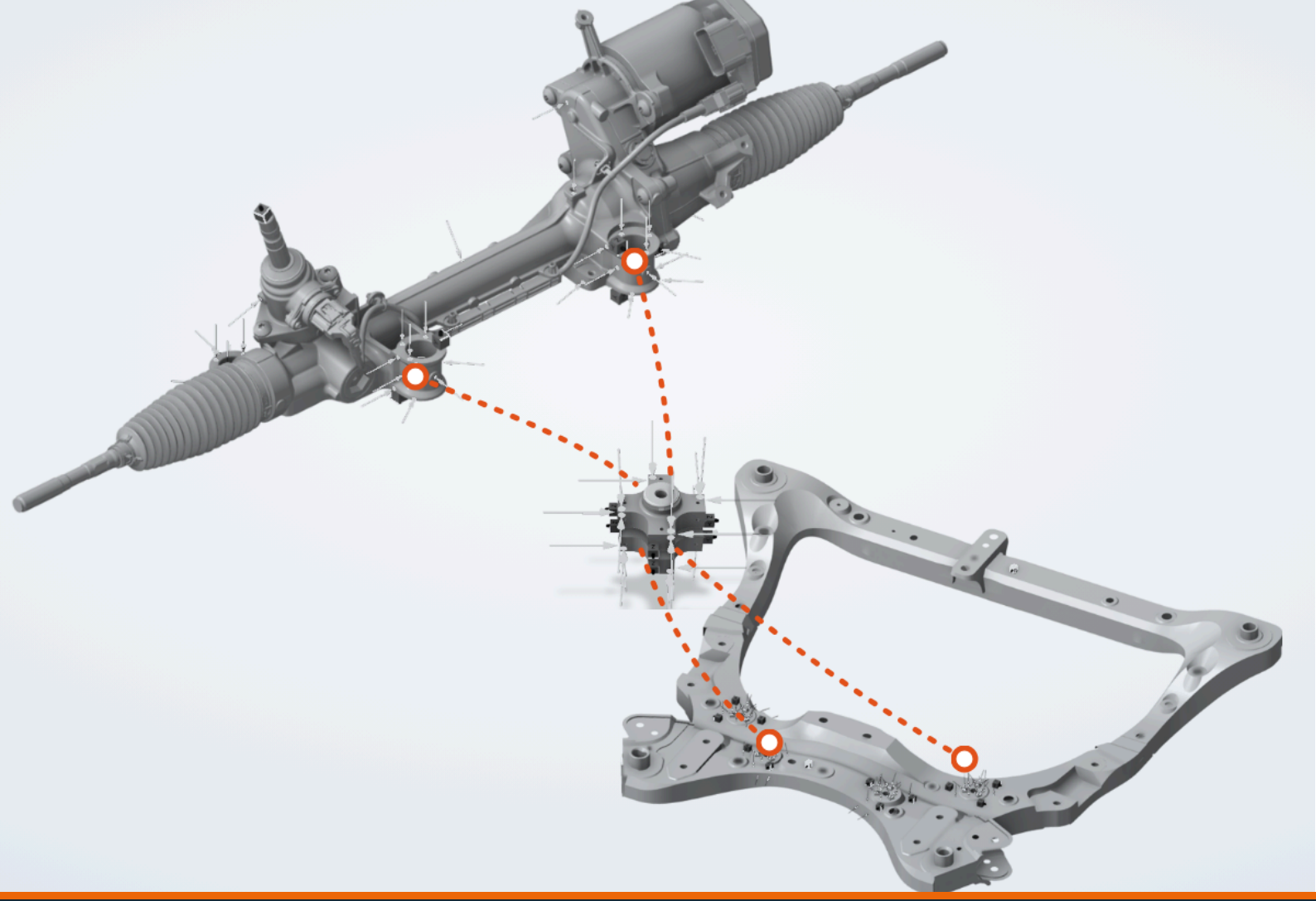


VIBES.technology

CASE STUDY

TOYOTA PREDICTS EPS NOISE TRANSMISSION FROM SEPARATELY MEASURED COMPONENTS

A virtual assembly of a steering gear, rubber mounts and subframe, validated against the physical assembly up to 1 kHz and then used to evaluate mount designs without new hardware

AT A GLANCE

CLIENT
Toyota Motor Corporation, automotive OEM

SYSTEM
EPS gear with integrated gearbox, four rubber mounts, subframe

PRODUCTS USED
DIRAC, SOURCE, COUPLE

KEY RESULT
A validated NVH model built from separately measured components, used to choose mount changes before building hardware

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Based on the peer-reviewed paper by VIBES.technology and Toyota: “Hybrid Modular NVH Engineering Applied to an Electric Steering Gear”, Aachen Acoustics Colloquium 2025.

Up to 1 kHz FRF validation
against the physical assembly

Up to 2.5 kHz identification
of mount dynamics, in all six degrees of freedom

0 hardware builds
needed for evaluating mount stiffness variants

AT A GLANCE

CLIENT	Toyota Motor Corporation
INDUSTRY SEGMENT	Automotive OEM, steering and chassis NVH
SYSTEM	Electric Power Steering (EPS) gear with integrated gearbox, four rubber mounts, subframe
VIBES.TECHNOLOGY PRODUCTS USED	DIRAC (FRF measurement, virtual points, quality checks) SOURCE (blocked forces) COUPLE (virtual assembly, parameter studies)
SOLUTIONS	Test-based modeling, Frequency Based Substructuring, Hybrid Modular Engineering
KEY RESULT	Toyota built a validated NVH model of the EPS installation from separately measured components. With it, the team found which mount changes reduce transmitted vibration, and in which frequency band, before building any physical model.

THE CHALLENGE

An Electric Power Steering (EPS) system combines mechanical and mechatronic subsystems in one unit. It is coupled to the chassis with mounts with a high dynamic stiffness and excites the structure over a wide frequency range. Electrification and lightweight design make this structure-borne noise harder to control. NVH (Noise, Vibration and Harshness) teams therefore need to know early how much EPS vibration reaches the vehicle structure.

The usual methods cannot give that answer both early and accurately. A transmission test needs the EPS, mounts and subframe assembled as hardware. That hardware is not available yet, and every mount change needs new parts and a new test. Finite element (FE) models are available earlier. However, they do not capture details such as damping at the interfaces, and they do not reach the required accuracy into the kHz range.

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Toyota wanted to predict EPS noise transmission by using component models, and to use that prediction for mount design decisions before hardware exists.

THE APPROACH

Toyota and VIBES.technology applied the VIBES Hybrid Modular Engineering (HME) process. Each component is characterized once, by test or by simulation. Its dynamics are described as frequency response functions (FRFs), including at the interfaces. The component models are then coupled in software with Frequency Based Substructuring (FBS). Together with the blocked forces that characterize the EPS, the coupled model predicts the operational vibration in the assembly.

TEST-BASED MODELS OF THREE COMPONENTS

In this case, all three components were measured separately with an impact hammer and triaxial accelerometers (Figure 1):

- EPS with integrated gearbox: three accelerometers at each of the four mounting points.
- Rubber mount: four accelerometers on each side, mounted on transmission simulators (the grey cross-shaped parts in Figure 1c).
- Subframe: three accelerometers at each of the four mounting points, plus separate validation sensors.

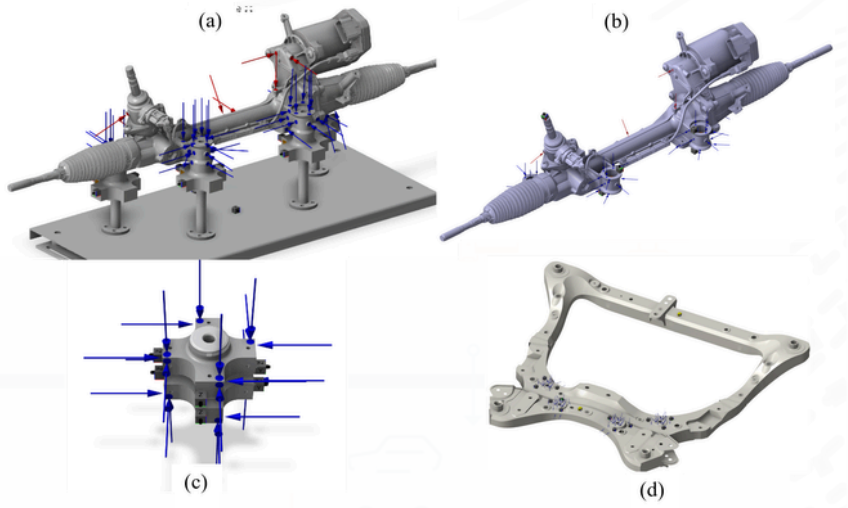


Figure 1: FRF measurement setups for (a, b) the EPS, (c) a rubber mount and (d) the subframe. Arrows show impact locations. The validation sensors on the subframe are highlighted in (d).

Sensors and impacts cannot be placed exactly at the point where two components connect. Virtual Point Transformation (VPT) in DIRAC solves this. It combines the measurements around each connection into one virtual point (VP) at the interface center, with three translations and three rotations. Each connection is then described by a 6-DoF (degree of freedom) model that is suitable for coupling.

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QUALITY CHECKS BEFORE COUPLING

The accuracy of the coupled model depends on the quality of the component models. Before coupling, DIRAC checked the virtual-point FRFs of every component for all degrees of freedom (Figure 2):

- Consistency: does the virtual point describe the measured motions and forces well?
- Reciprocity: is the FRF from point A to point B equal to the FRF from B to A?
- Passivity: does the component only absorb energy, and never generate it?

The EPS models showed high reciprocity and high force and response consistency. A consistency above approximately 0.7 is sufficient for a reliable assembly up to several kHz.

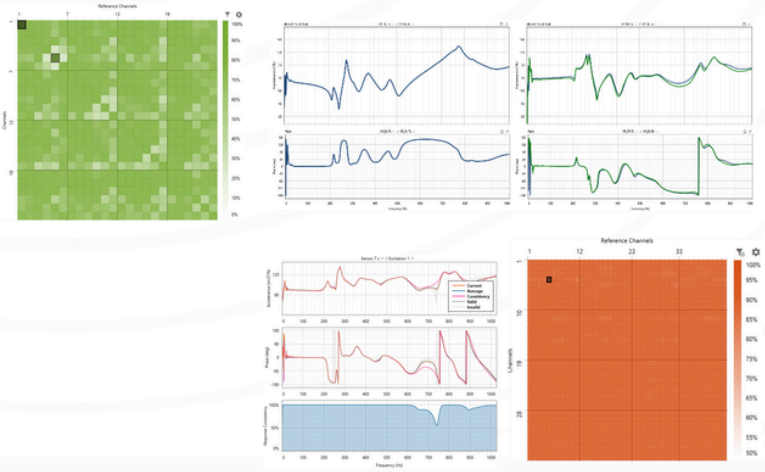


Figure 2: Quality checks in DIRAC. Top: reciprocity matrix (green), passivity of a driving-point FRF, reciprocity of a translation-to-rotation cross FRF. Bottom: response consistency of one channel, and the force and response consistency matrix (orange).

The value of using measured component models is demonstrated with the rubber mount. Its dynamic transfer stiffness was measured in all six degrees of freedom (Figure 3). The internal resonances of the mount are captured up to almost 2.5 kHz. These values come from measurement, not from assumed material properties.

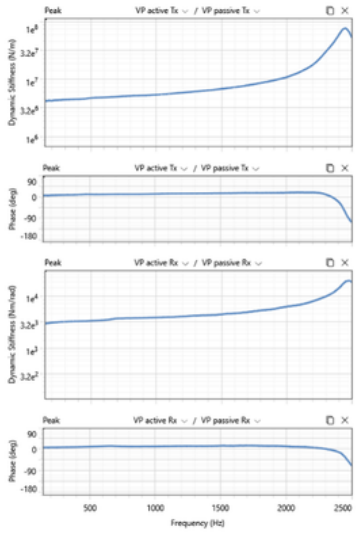


Figure 3: Measured 6-DoF dynamic transfer stiffness (magnitude and phase) of one of the rubber mounts, from the active-side to the passive-side virtual point. The internal mount resonances are captured up to almost 2.5 kHz.

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VIRTUAL ASSEMBLY WITH FBS

FBS couples the component FRFs with two conditions at each interface. Both sides move together (compatibility), and the interface forces are in balance (equilibrium). The result is the FRF matrix of the complete EPS, mount and subframe assembly, without the need to bolt any hardware together.

A prediction of operational vibration needs two descriptions of the EPS. The first is its FRF model, which is part of the assembly. The second is its excitation, described by blocked forces. Blocked forces describe the source independently of its environment, so they apply directly to the virtual assembly. In this case, the blocked forces were identified in-situ on a test bench with the X-DoF algorithm in SOURCE. Source characterization is the topic of a separate case study.

THE RESULTS

THE VIRTUAL ASSEMBLY MATCHES THE PHYSICAL ASSEMBLY

For validation, the team built the physical assembly once. Impact excitations on the steering gear were used as artificial load cases. The FRFs from these points to validation sensors on the subframe were calculated with the virtual assembly and measured on the hardware. The predicted FRF showed very high similarity to the validation measurement (Figure 4). Across the full 0 to 1000 Hz range shown, the coupled model reproduces the resonance frequencies and the overall level.

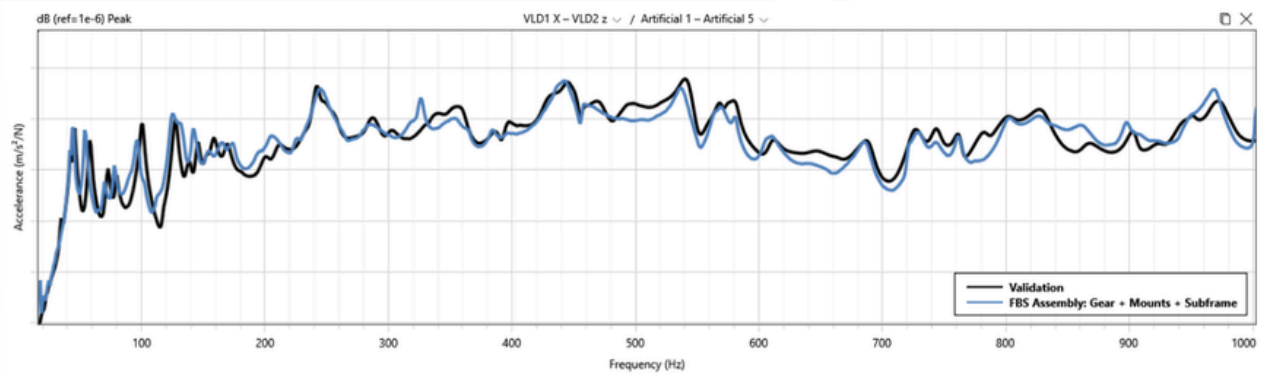


Figure 4: FRF from artificial excitations on the steering gear to a validation sensor on the subframe. Black: measured on the physical assembly. Blue: FBS assembly of the separately measured gear, mounts and subframe.

This is the central finding of the case: a model assembled only from separately measured components, using VIBES.technology's DIRAC and COUPLE, reproduces the dynamic behavior of the physical assembly up to 1 kHz.

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MOUNT DESIGN DECISIONS WITHOUT NEW HARDWARE

Next, the team applied the EPS blocked forces to the validated assembly. This blocked force transfer path analysis (TPA) predicts the operational vibration at a validation accelerometer on the subframe. In COUPLE, the translational and rotational mount stiffnesses were then varied as a percentage of the baseline. Figure 5 shows the nominal mounts and stiffness reductions of 10%, 50% and 90%.

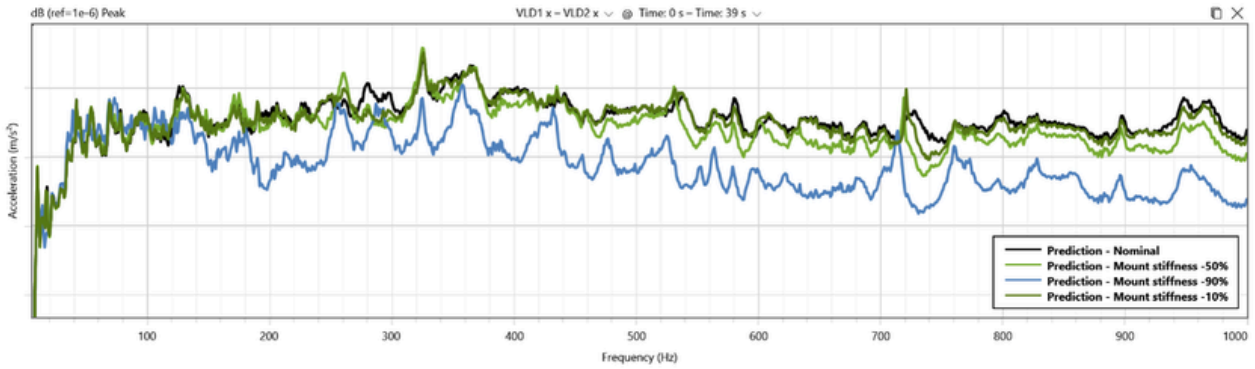


Figure 5: Blocked force TPA prediction at a subframe validation accelerometer for the mount stiffness variants.

Softer mounts reduce the subframe vibration over most of the frequency range. The reduction is clear in the 500 to 1000 Hz band, and much smaller in the 20 to 500 Hz band. For this design, softer mounts therefore improve the acoustic performance mainly for high-frequency EPS excitation. The team reached this conclusion without building any mount variant.

Each variant is a new calculation, not a new test. COUPLE only calculates the parameter combinations that are requested. A study can therefore include tens of thousands of variants without loss of performance.

KEY RESULTS

- Validated virtual assembly: coupled FRFs from three separately measured components matched the physical assembly up to 1 kHz.
- Measured mount dynamics: 6-DoF mount stiffness measured up to almost 2.5 kHz.
- Clear design direction: softer mounts mainly reduce vibration from 500 to 1000 Hz, with a much smaller effect from 20 to 500 Hz.
- No additional hardware models: no stiffness variant had to be built or tested.

CASE STUDY

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The case shows that the workflow gives much greater predictive accuracy than was previously possible. Because test-based component models can be reused digitally, it also significantly reduces development time and cost.

WHAT THIS MEANS FOR NVH AND CAE TEAMS

For NVH engineers and managers, the main change is timing. Components are characterized once and reused across variants and programs. Transmission questions can then be answered before the first full prototype. In this case, the target was a sensor on the subframe. In a full-vehicle study, it can be a seat rail accelerometer or a cabin microphone.

For CAE engineers, the case shows what measured models add for components that are difficult to simulate. An example is a rubber mount with internal resonances up to 2.5 kHz. All components in this case were measured.

Teams that wait for the first physical assembly make their mount and bracket decisions late, and only for the few variants they can build. In this case, Toyota's engineers evaluated stiffness variants on a validated virtual assembly before any of these variants were physically needed.

FURTHER READING

This case study describes the substructuring part of the work. The full method, the equations and the source characterization results are in the peer-reviewed paper by VIBES.technology and Toyota:

E. Pasma, W. Schüttler (VIBES.technology) and H. Kamano (Toyota Motor Corporation), “Hybrid Modular NVH Engineering Applied to an Electric Steering Gear”. Aachen Acoustics Colloquium (AAC) 2025.

Learn the methods behind this case at the VIBES Academy:

www.vibestechnology.com/academy