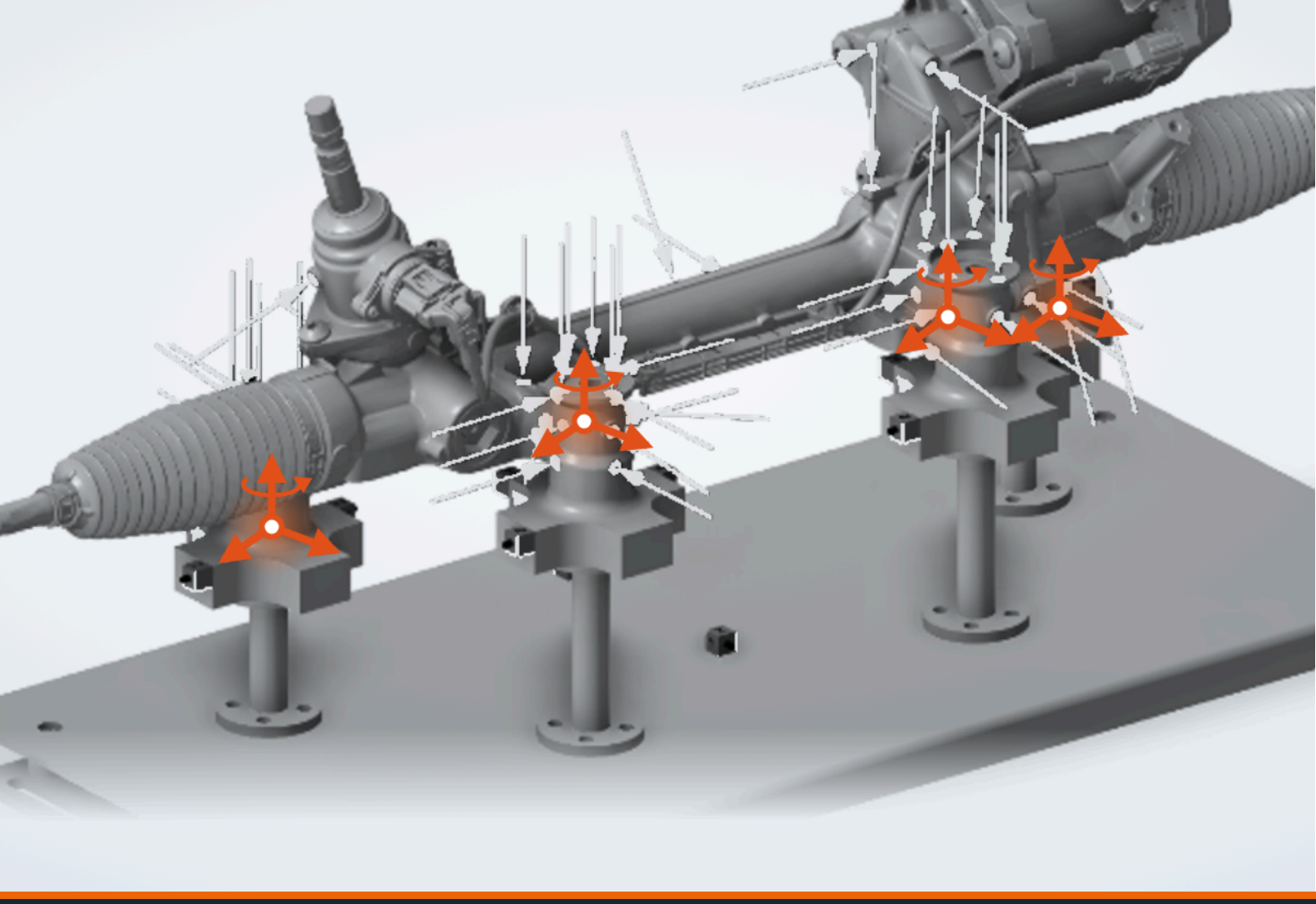


VIBES.technology

CASE STUDY

TOYOTA TURNS AN EPS TEST-BENCH MEASUREMENT INTO A REUSABLE SOURCE DESCRIPTION

In-situ blocked forces accurately identified with the X-DoF algorithm, validated on the test bench and then used in a virtual EPS, mount and subframe assembly

AT A GLANCE

CLIENT
Toyota Motor Corporation, automotive OEM

SOURCE
Electric Power Steering (EPS) gear with integrated gearbox, on a blocked-force test bench

PRODUCTS USED
DIRAC, SOURCE, COUPLE

KEY RESULT
6-DoF blocked forces at all four EPS mounts, validated on the bench and reused as the source in a virtual assembly

CASE STUDY

TOYOTA TURNS AN EPS TEST-BENCH MEASUREMENT INTO A REUSABLE SOURCE DESCRIPTION

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.

Automatic DoF selection
for accurate blocked force identification without under- or overfitting

Accurate prediction
of blocked forces and moments, matching the measured response into the kHz range

1 measured source
reused in variant studies of a virtual vehicle assembly

AT A GLANCE

CLIENT	Toyota Motor Corporation
INDUSTRY SEGMENT	Automotive OEM, steering and chassis NVH
SOURCE	Electric Power Steering (EPS) gear with integrated gearbox, on a blocked-force test bench
VIBES.TECHNOLOGY PRODUCTS USED	DIRAC (FRF measurement, virtual points, quality checks) SOURCE (in-situ blocked forces, X-DoF algorithm, on-board validation) COUPLE (reuse in a virtual assembly)
SOLUTIONS	Source Characterization, Blocked Force TPA, Hybrid Modular Engineering
KEY RESULT	Toyota obtained a 6-DoF blocked-force description of the EPS at all four mounts. The prediction matched the measured response at an on-board validation sensor. The same blocked forces then served as the source in a virtual assembly with a different receiver and were used for multiple variant studies.

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 vehicle structure over a wide frequency range. To predict how much of this vibration reaches the vehicle, NVH (Noise, Vibration and Harshness) teams need a description of the EPS as a source.

Interface forces measured on a test bench are not that description. They depend on the bench, and they change as soon as the EPS is mounted in a vehicle. The source description must describe the EPS independently of its environment, so that it stays valid in any assembly.

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Blocked forces meet this requirement. They are the interface forces that the EPS would apply if its mounts were fixed rigidly. They are calculated indirectly: from responses measured close to the mounts, and from the measured FRFs of the setup. This is an inverse calculation, and it has a well-known difficulty. With too few interface degrees of freedom, the forces are under-predicted. With too many, measurement noise is amplified and the forces are over-predicted. The usual fix is manual tweaking of the force identification process, such as matrix regularization. That makes the result depend on the settings the engineer chooses.

Toyota wanted blocked forces for the EPS that are reliable over the full frequency range, and that can be carried over to a vehicle assembly without measuring the source again.

THE APPROACH

THE EPS ON A BLOCKED-FORCE TEST BENCH

In this case, the EPS with integrated gearbox was installed on a test bench at its four mounting points (Figure 1). Each mounting point had three triaxial accelerometers. FRFs of the setup were measured with an impact hammer.

The Virtual Point Transformation (VPT) in DIRAC combines the sensors and impacts around each mount into one virtual point (VP) at the center of the interface. Each VP has six degrees of freedom (DoF): three translations and three rotations. The four mounts therefore give 24 interface DoFs: forces and moments in all directions.

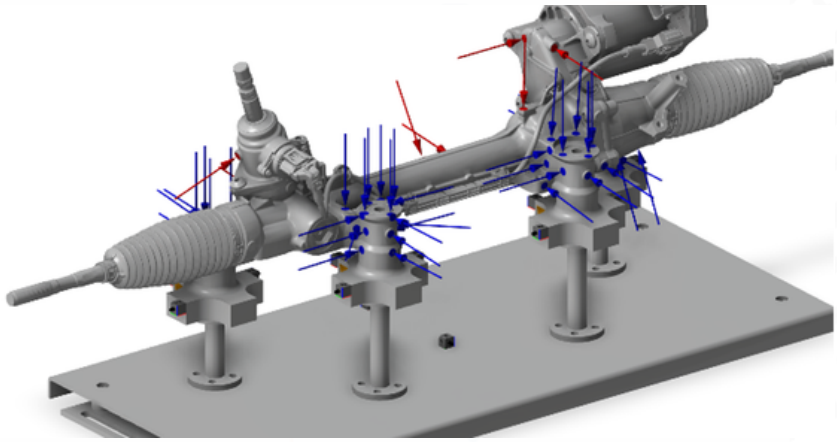


Figure 1: The EPS with integrated gearbox on the blocked-force test bench. Arrows show the impact locations. Accelerometers are placed around each of the four mounts.

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QUALITY CHECKS ON THE FRFS

The blocked forces can only be as accurate as the FRFs used to calculate them. DIRAC checked the virtual-point FRFs of the EPS 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 structure only absorb energy, and never generate it?

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

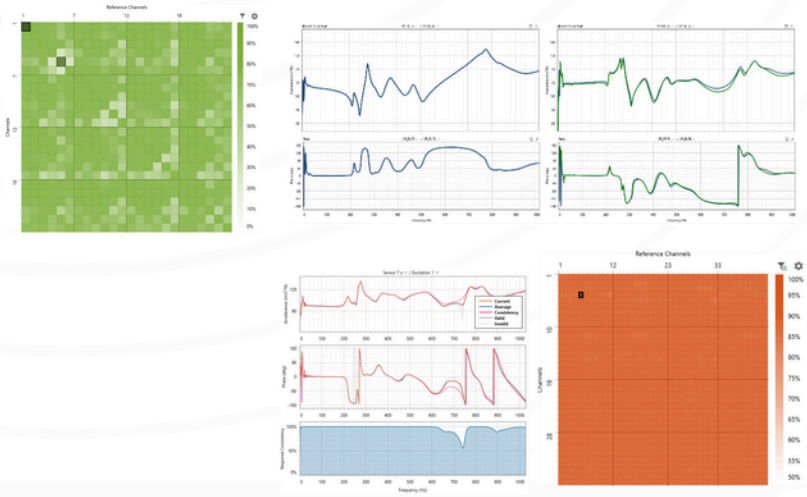


Figure 2: Quality checks in DIRAC. Top: reciprocity matrix (green), passivity of a driving-point FRF, reciprocity of a translation-to-rotation cross FRF. Bottom: response consistency of one channel, and the force and response consistency matrix (orange).

IN-SITU BLOCKED FORCES WITH THE X-DOF ALGORITHM

With the EPS running on the bench, the responses at the interface sensors were recorded. SOURCE then calculated the blocked forces from these operational responses and the measured FRFs. With this in-situ method, the forces are identified directly on the assembled test bench.

For the inverse calculation, the team used the patented X-DoF algorithm. At each frequency, X-DoF selects the subset of interface DoFs that gives the smallest residual error. It needs no manual tweaking of the force identification process. The result is a set of physically plausible blocked-force spectra that can be transferred to other assemblies.

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THE RESULTS

THE PREDICTION MATCHES THE MEASURED RESPONSE

The blocked forces were validated with an on-board validation sensor: an accelerometer on the test setup that was not used to calculate the forces. The blocked forces predict the response at this sensor, which is then compared with the measured operational response (Figure 3, top).

Both X-DoF and the conventional matrix inverse predict the validation response accurately over most of the range. A stand-still measurement, with the EPS not running, shows the level that comes from sensor noise alone. At low frequencies, the conventional matrix inverse follows this noise level: it fits noise, not the source. X-DoF does not.

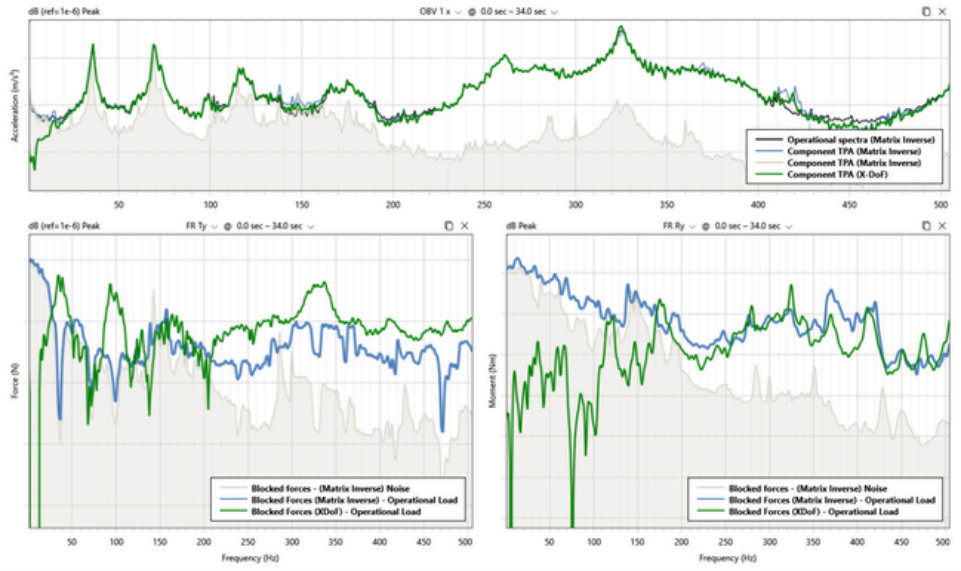


Figure 3: Top: on-board validation. Measured operational response (black), prediction with the conventional matrix inverse (blue) and with X-DoF (green), and the prediction from a stand-still measurement (gray, sensor noise). Bottom: identified blocked force (left) and blocked moment (right) at one mount, with the noise level in gray. The results extend well into the kHz range; 0 to 500 Hz is shown for clarity.

FORCES BELOW THE NOISE FLOOR

The difference is largest in the forces themselves (Figure 3, bottom). At the lowest frequencies, where sensor noise dominates, the conventional matrix inverse calculates forces based on noise. That results in a large over-prediction. X-DoF however identifies forces and moments below the noise floor, most clearly for the moments. It keeps only the DoFs that give reliable results in each frequency range.

CASE STUDY

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ONE SOURCE DESCRIPTION, VARIOUS RECEIVER VARIANTS

A blocked-force prediction needs two descriptions of the EPS: its FRF model and its blocked forces. Both came from the test bench. In the next step, they were combined with measured models of the rubber mounts and the subframe in a virtual assembly (FBS) in COUPLE. The EPS was not measured again on the subframe. Using the same blocked forces, the team predicted subframe vibration for several mount stiffness variants (Figure 4). The substructuring part of this work is described in a separate case study.

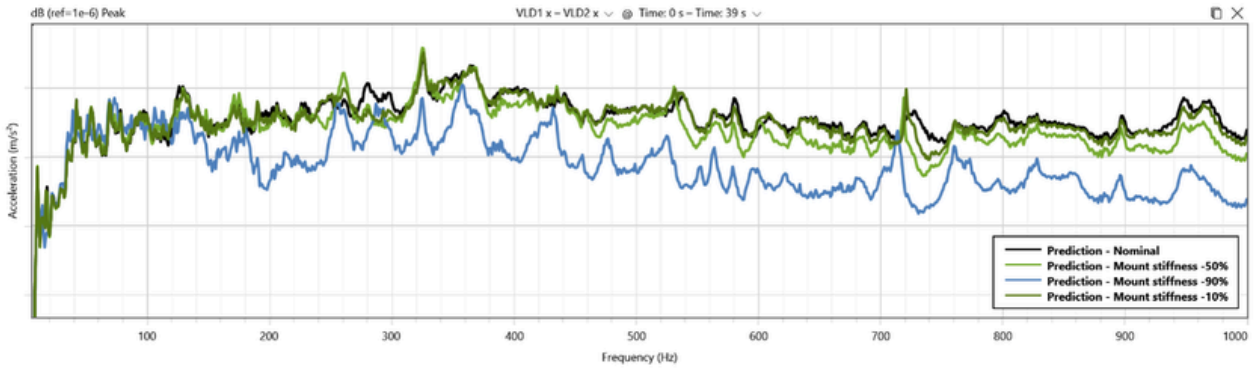


Figure 4: Blocked force TPA prediction at a subframe validation accelerometer, using the EPS blocked forces from the test bench in the virtual EPS, mount and subframe assembly. The graph shows nominal mounts and stiffness reductions of 10%, 50% and 90%.

KEY RESULTS

- Complete source description: 6-DoF blocked forces and moments at all four EPS mounts, well into the kHz range.
- Validated on the bench: the prediction matched the measured independent on-board validation response.
- No noise fitting: X-DoF identified forces and moments below the noise floor, where the conventional matrix inverse over-predicted.
- No manual settings: X-DoF selected the relevant interface DoFs per frequency, without matrix regularization.
- Reused, not re-measured: the same blocked forces served as the source in a virtual assembly with various receiver variants.

The case shows that the X-DoF blocked-force method improves the transferability of source descriptions from the test bench to different assemblies.

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WHAT THIS MEANS FOR NVH AND CAE TEAMS

For NVH test engineers, the source is measured once, on a bench, and the result stays valid in other assemblies. X-DoF removes the manual regularization step, so the forces no longer depend on the settings an engineer chooses.

For NVH managers and suppliers, the blocked forces describe only the EPS. The source and the receiver can therefore be assessed separately, and a component supplier can deliver a source description that the vehicle team can use directly.

For CAE engineers, blocked forces are the load input for a receiver model. In this case the receiver was a test-based assembly. The same forces can be applied to other, numerical receiver models, so load cases for the EPS come from measurement instead of assumptions.

Teams that still use interface forces from a bench, or tune the regularization by hand, get forces that depend on the bench or on the engineer. Every new vehicle then needs a new measurement. In this case, Toyota measured the EPS once and used the result in various virtual vehicle assemblies.

FURTHER READING

This case study describes the source characterization part of the work. The full method, the equations and the substructuring 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.

The X-DoF algorithm is described in:

P.E. Bofinger et al., "X-DoF: Automatic Degree-of-Freedom Subset Selection for Inverse Blocked Force Characterization". Journal of Vibration and Acoustics 147(1), 011002, 2025.

Related case study: *"Toyota predicts EPS noise transmission from separately measured components" (substructuring).*

Learn the methods at the VIBES Academy: www.vibestechnology.com/academy