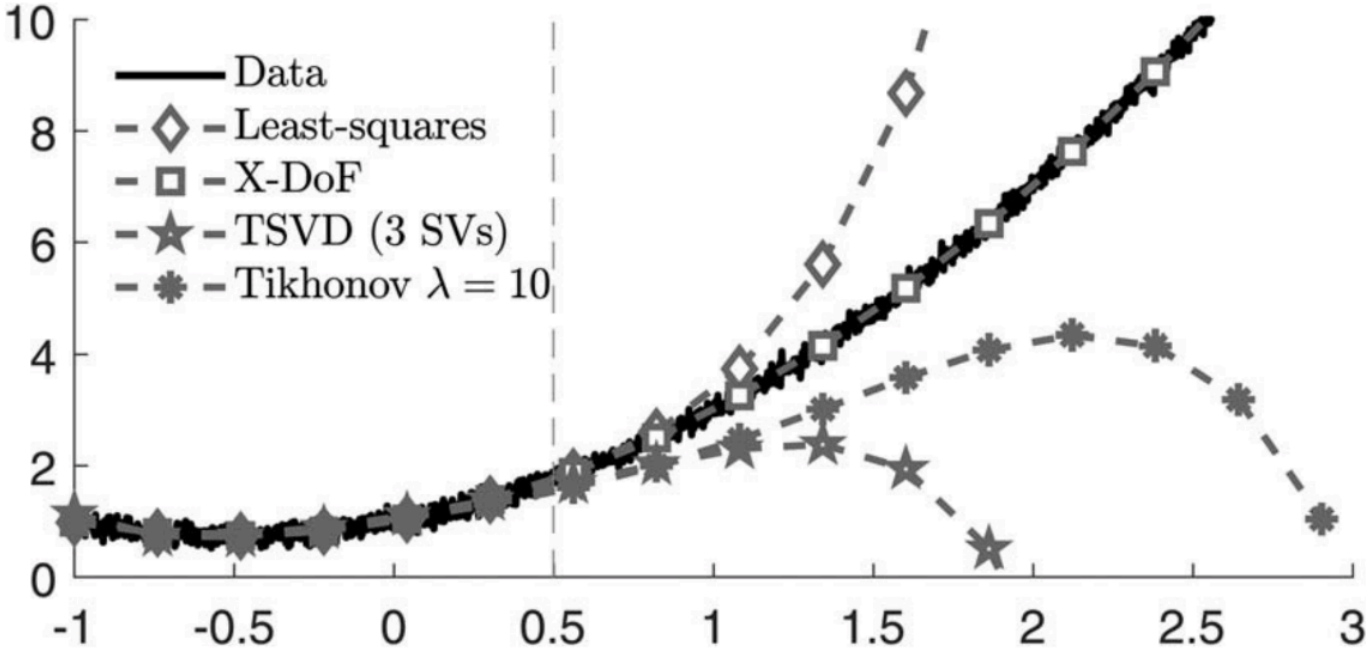


VIBES.technology

CASE STUDY

THE PROBLEM WITH MATRIX REGULARIZATION IN IN-SITU BLOCKED FORCE IDENTIFICATION

AT A GLANCE

TEST OBJECT
Full vehicle, blocked forces at all four wheel hubs at the same time

PRODUCTS USED
SOURCE with the X-DoF algorithm

APPLICATION
Structure-borne road noise: in-situ blocked force identification per ISO 20270

KEY RESULT
Only X-DoF found negligible force on the non-excited wheel and reconstructed the hammer force on the excited one, with a single setting

CASE STUDY

THE PROBLEM WITH MATRIX REGULARIZATION IN IN-SITU BLOCKED FORCE IDENTIFICATION

X-DoF, VIBES' patented inverse algorithm, uses a single setting and gives more accurate force estimates than matrix regularization, in both classic matrix inverse and in-situ blocked force characterization. This case study shows the evidence from a full-vehicle measurement: blocked forces identified at the wheel hubs of all four wheels at the same time, for different excitation cases.

THE APPROACH

To show the difference in accuracy, this study changes what counts as an operational measurement. Normally that would be the vehicle driving. Here, the impact hammer already used for the FRF measurements simulates the operational condition instead. Hitting the wheel rim gives the vehicle a single, known excitation. The resulting indicator sensor accelerations are used to compute the blocked force at the wheel hub and the target responses, exactly as with driving measurements. This is called artificial excitation.

With the in-situ method, the vector sum of the XYZ blocked forces on the excited wheel should therefore match the hammer force (and moments), and the non-excited wheels should show zero blocked force. How well the hammer force is reconstructed, and how small the forces on the other wheels are, gives an objective comparison between matrix regularization settings and X-DoF.

THE SET-UP

The measurement setup consists of three acceleration sensors per wheel hub. Small transmission simulators in the form of pyramids are mounted to the wheel rim (Figure 1). They allow the wheel to be excited well in all directions, which gives a good blocked force identification matrix.

All four wheels are measured, because cross-talk (for example, vibration of the left wheel measured on the right wheel) would distort the blocked force identification if only single wheels were measured.

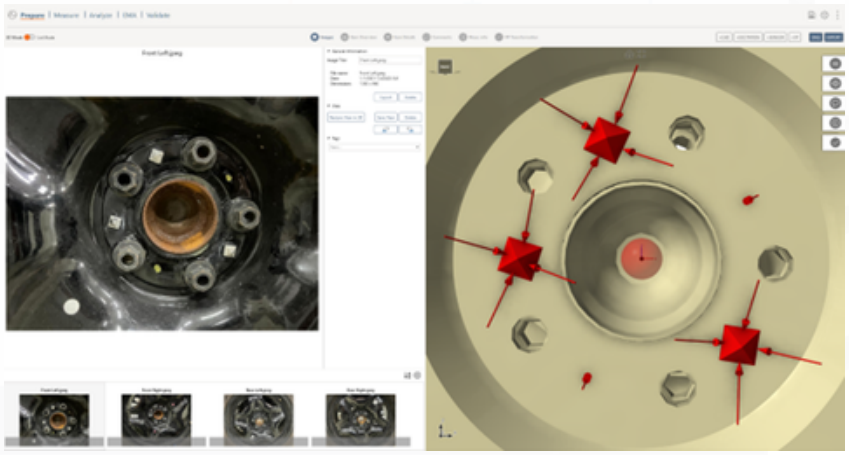


Figure 1: Example of wheel instrumentation setup.

THE PROBLEM WITH MATRIX REGULARIZATION IN IN-SITU BLOCKED FORCE IDENTIFICATION

Target sensors are seat rail accelerometers and cabin microphones.

The measurement was performed on the full vehicle, with some ambient noise reaching the microphones. Two impact hammers were used, one with a rubber tip and one with a nylon tip. Our software applies high-pass and low-pass filters to the combined measurement to improve the FRF estimate over a wider frequency range.

Blocked forces are determined with the Virtual Point Transformation (VPT), which is needed for accurate blocked forces and moments. The virtual point is the sphere in the middle of Figure 1.

The forces and moments are computed at the center of the sphere. Because the impact locations relative to the virtual points matter, photos were taken of the setup and used to fine-tune the locations and orientation of the pyramids.

RESULT I

We start with the end result. A good blocked force identification should reconstruct the vibration measured at the target locations, such as the cabin microphones and the seat rail. This check is called on-board validation and is a quality indicator in ISO 20270:2019. Figure 2 shows the match for three processing variants, with the validation curve in black.

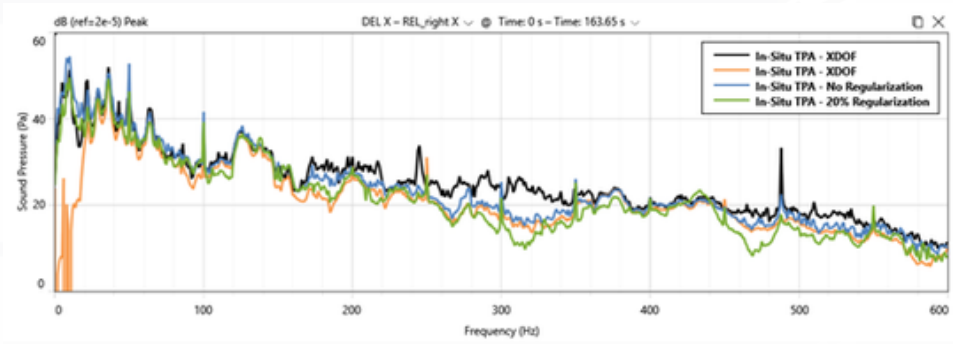


Figure 2: Average onboard validation results of the cabin microphones.

The three processing settings are:

1. **No regularization,** i.e. using all singular values in matrix inversion
2. **20% regularization,** i.e. taking a subset of the matrix singular values.
3. **X-DoF** instead of matrix regularization parameters.

All three settings match the validation curve reasonably well. From 160 Hz to 350 Hz none of them match, because the microphones also recorded ambient noise during the artificial excitation measurement.

THE PROBLEM WITH MATRIX REGULARIZATION IN IN-SITU BLOCKED FORCE IDENTIFICATION

Below 20 Hz, the X-DoF result drops off, which indicates that it cannot find a valid blocked force set that reconstructs the measured response. More on this later. Otherwise, no regularization seems to perform best overall.

So which method is best? *No regularization at all? Really?*

The computed blocked forces answer that. Figure 3 shows the vector sum of the blocked forces identified on the Front Right wheel hub while the Rear Right wheel was hit. Ideally, no force should be found on the Front Right wheel, because the only excitation was applied elsewhere.

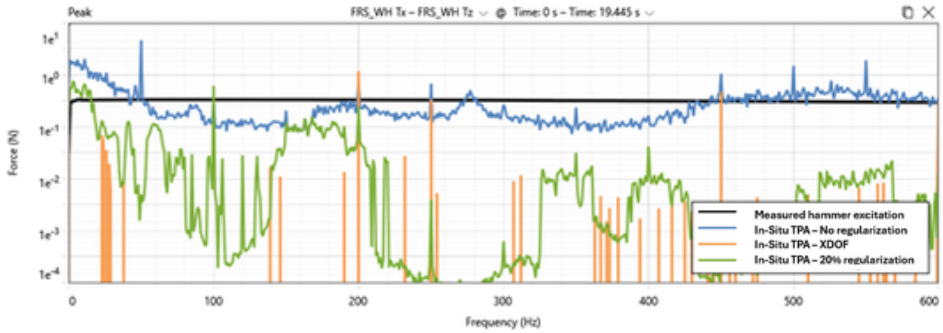


Figure 3: Impact force reconstruction on Front Right wheel with excitation on Rear Right wheel.

On average, the impact hammer applied roughly 0.3 N of force over the frequency range of 0 to 600 Hz. On the non-excited wheel, the figure shows that:

1. Without matrix regularization, the in-situ computation finds forces of about the same magnitude as the hammer force, and in several frequency ranges even higher, on a wheel that was not excited. The plain matrix inverse produces errors as large as or larger than the force actually applied to the vehicle.

2. Applying 20% regularization in the computation clearly improves the force estimate (in this figure, lower being better) by typically one order of magnitude or more. However, not consistently over the full frequency range: below 20 Hz and around 180 Hz, the false force still has a similar amplitude.

3. X-DoF indicates that no excitation is present on the Front Right wheel while the Rear Right wheel is hit, which is correct.

Only X-DoF produces the correct, negligible force estimate.

THE PROBLEM WITH MATRIX REGULARIZATION IN IN-SITU BLOCKED FORCE IDENTIFICATION

RESULT II

Because the in-situ method is a least-squares method, on-board validations such as Figure 2 are typically best when all degrees of freedom (DoF) are used. The more blocked forces you add, the better it can fit the data, but, as seen, the resulting forces are also increasing, yielding non-physical results. This effect is called over-fitting. Matrix regularization can't solve this issue, as any setting still keeps the full amount of DoF and only regulates their linear (in)dependence.

X-DoF takes a different approach. It searches for the blocked forces that are actually active in the matrix and operational conditions, which is why it finds negligible forces on the non-excited wheels in Figure 3.

Now consider the load case with the excitation collocated with the Front Right wheel. Figure 4 shows the reconstructed impact hammer force.

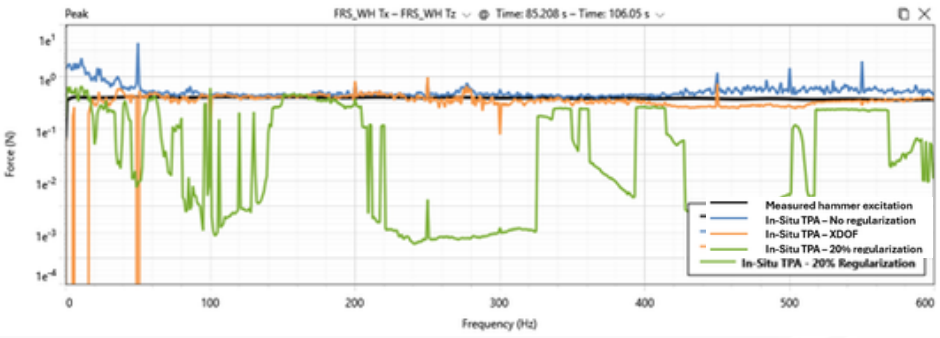


Figure 4: Impact force reconstruction on Front Right wheel with collocated excitation.

X-DoF reconstructs the applied force very well, with very little overshoot. The blue curve, estimated without matrix regularization, shows a clear overshoot below 50 Hz: forces that improve the on-board fit but are not physically real.

Effectively, our blocked force model/identification matrix suffers from too little excitation energy during the FRF testing and too high ambient disturbances in the operational measurement. The indicator sensors run into their noise floor during FRF testing at these low frequencies, and while matrix regularization still uses the matrix to fit the target responses, X-DoF finds the correlation to the operational test invalid and has the forces drop to zero, showing the model cannot predict the noise measured on the onboard validation.

Note that 20% matrix regularization improved the force estimate when a different wheel was hit, but gave poor estimates on the collocated wheel, worse than no regularization at all. Hence, as also proven in our X-DoF paper [1], matrix regularization causes bias errors, and, therefore, there is no regularization parameter that gives the correct result when suffering from overfitting.

THE PROBLEM WITH MATRIX REGULARIZATION IN IN-SITU BLOCKED FORCE IDENTIFICATION

No regularization parameter matches the X-DoF solution. Regularization settings are also chosen freely per TPA, so different engineers apply different settings. Regularization therefore not only misses the right blocked forces; its results also vary from engineer to engineer. X-DoF uses one setting, which removes the influence of the user.

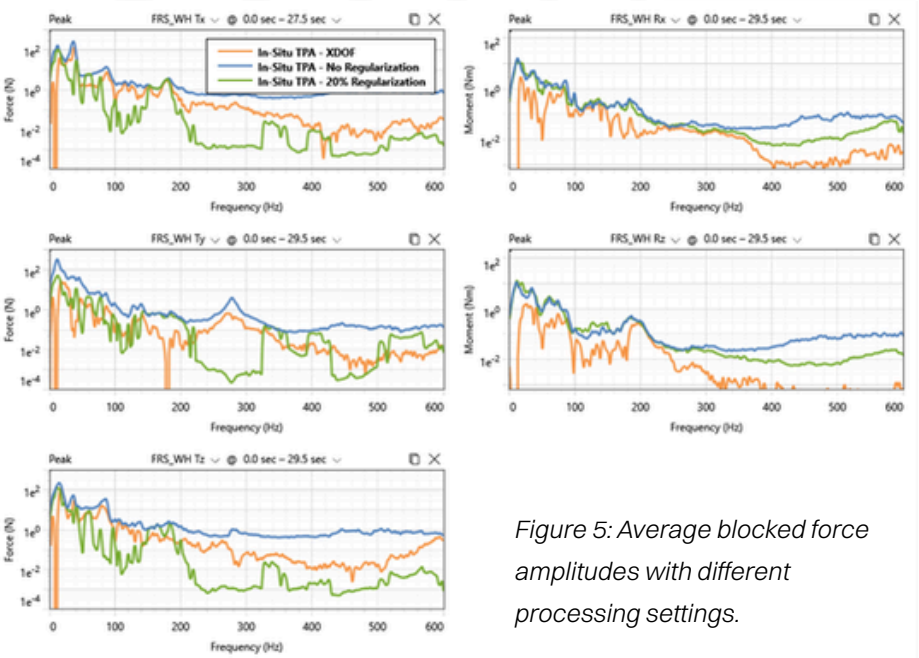


Figure 5: Average blocked force amplitudes with different processing settings.

CONCLUSIONS

Plain matrix inversion produced forces that do not exist. On the non-excited front right wheel, it estimated forces as large as, or larger than, the roughly 0.3 N hammer force applied to the rear right wheel. 20% regularization reduced these false forces by about an order of magnitude, but not below 20 Hz or around 180 Hz, and on the excited wheel it gave worse estimates than no regularization at all. No regularization setting matched X-DoF in both load cases.

X-DoF found the right forces in both cases: negligible force on the non-excited wheel, and the applied hammer force on the excited wheel with little overshoot. Where the data could not support a solution, it showed that too. Below 20 Hz, where the indicator sensors were at their noise floor, the X-DoF forces dropped to zero instead of fitting noise.

The study also shows that a good on-board validation does not prove the forces are right. The closest fit came from no regularization, the setting with the least physical forces, which is a sign of over-fitting. And because X-DoF uses a single setting, its results do not depend on the engineer running the analysis.

[1] P. Bofinger et al., "X-DoF: automatic degree of freedom subset selection for inverse blocked force characterization", ASME Journal of Vibration and Acoustics.