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CASE STUDY

VOLVO CARS GETS THE SAME E-COMPRESSOR BLOCKED FORCES, MOUNTED AND FREELY SUSPENDED

AT A GLANCE

CLIENT
Volvo Cars, automotive OEM

APPLICATION
Electric refrigerant compressor (EC), structure-borne noise from 0 to 500 Hz

PRODUCTS USED
DIRAC, SOURCE

KEY RESULT
In-situ and freely suspended tests gave the same blocked forces, so the compressor can be characterized either way

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This case study comes from VIBES.technology's early collaboration with automotive partners to test its methodology in practice. It shows an independent source characterization of an electric refrigerant compressor (EC), carried out with Volvo Cars.

THE CHALLENGE

Without the masking noise of a combustion engine, auxiliary components become audible in electric vehicles. One of these is the electric refrigerant compressor (EC). Besides controlling the cabin temperature, the EC cools the battery and power electronics during operation, and especially during fast charging.

Mounting concepts for the EC differ across the industry. In this case study, the EC is rigidly mounted with three connection points to a bracket. The bracket is mounted with three rubber bushings to the e-motor.

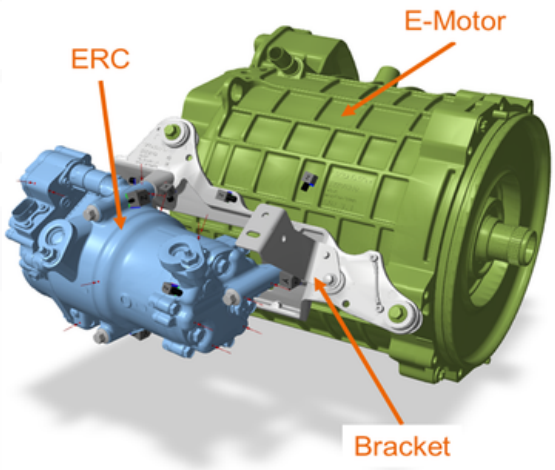


Figure 1: DIRAC screenshot of the CAD geometries illustrating the mounting concept of the EC.

SOURCE CHARACTERIZATION APPROACH

Because the frequency range of interest is low (0-500 Hz), the blocked forces can be described at the compressor's center of gravity (CoG). This assumes the EC behaves as a rigid body in this range, which was verified by identifying the compressor's first eigenmode. Describing the source at the CoG rather than at the connection points also avoids amplifying measurement noise through poor matrix conditioning. Two approaches were used to determine the blocked forces :

- EC mounted: In-situ characterization using a matrix inversion procedure;
- EC freely suspended: blocked forces calculated from 'free vibrations'.

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For both applications, the virtual point transformation (VPT) was used to express the blocked forces in the CoG. Next to that, the VPT ensures the transferability of the blocked forces, to the current vehicle or to another compressor/receiver combination.

The validation of the two sets of blocked forces was done with a blocked force transfer path analysis (TPA) synthesis to a structural response point and to a microphone in the vehicle's interior.

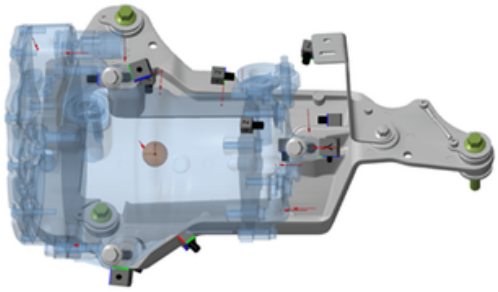


Figure 2: DIRAC screenshot of the compressor and the bracket with a virtual point in the center of gravity.

EC MOUNTED

The EC is rigidly mounted onto a bracket, which is in turn resiliently mounted to the front electric motor. The e-motor is also resiliently mounted to the vehicle's body. To obtain blocked forces, operational measurements and FRF measurements are conducted with the same set of sensor positions. Two accelerometers per connection point on the bracket were used as indicator sensors for the matrix inversion. In addition to that, sensors on the seat rail and microphones at the driver's ear were used for validation.
Operational measurements were conducted for distinct constant speeds from 800 RPM up to 9000 RPM and for linear sweeps over the full range. The operational conditions were recorded at the sensor and microphone positions and later transformed into the frequency domain.

Next, an impact measurement was conducted for impact points on the compressor housing as shown in ***Fig. 3***. These impacts are transformed into virtual point forces and moments in the center of gravity of the compressor. This yields the transfer function Y_{32}^{AB} from the center of gravity to the validation points and Y_{42}^{AB} to the indicator points on the bracket.

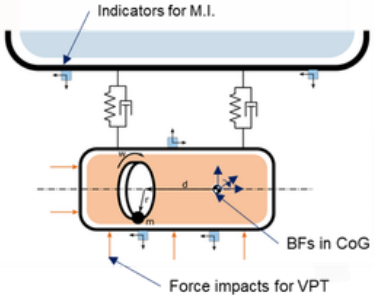


Figure 3: Schematic drawing of the EC mounted condition for the in-situ blocked force characterization.



Figure 4: This picture shows the mounted condition of the EC in the vehicle. One can see the top right connection point of the EC to the bracket which is equipped with two sensors.

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The operational and FRF measurements give the validation signal u_3 and responses u_4 of the indicator sensors at the brackets in the frequency domain, and the FRFs from the CoG Y_{42}^{AB} and Y_{32}^{AB} to the indicator and validation points.

With these results, one can calculate the blocked forces and conduct an on-board validation. No regularization was needed, because describing the source at the CoG keeps the matrix well conditioned:

$$f_2^{bl} = \left(Y_{42}^{AB}\right) + u_4$$

These forces can now be used to predict u_3^{pred} at the validation points inside the car. These predictions can be compared to the measured signal. This procedure is called an on-board validation and produces typically good results. The predictions are calculated as follows:

$$u_3^{pred} = Y_{32}^{AB} f_2^{bl}$$

The predictions were validated at the driver's ear microphone and at a sensor at the seat rail. The results in Fig. 5 show that the first order of the compressor at 4000 RPM is dominant in the driver's cabin. One can observe that the blocked force prediction matches the first order quite well. The prediction also gives response levels where the measured signal is below the noise floor.

As mentioned, the on-board validation typically produces quite good results. To further assess the transferability of the blocked forces, we determined a second set of blocked forces under freely suspended conditions and applied these to the vehicle FRF.

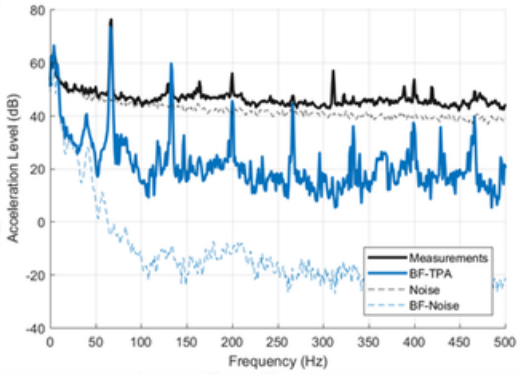


Figure 5: The on-board validation for the seat rail sensor. The results are shown for the state at 4000 RPM.

The purpose is to prove the transferability of blocked forces.

EC FREELY SUSPENDED

For the freely suspended measurement, the EC was dismounted from the vehicle and suspended by rubber ropes. This time, six sensors are placed on the EC itself. Again, operational tests and FRF measurements were conducted with the same set of sensors. For the operational tests, the same operational states were recorded as in the mounted approach.
For the FRF measurement, the EC was turned off again, and the impacts were placed on the EC housing.

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As a result of the operational and the FRF measurements, one obtains the u^{free} of the indicator sensors in the frequency domain and the FRFs from the CoG Y_{22}^{A} to the indicator points.

With these results, one can calculate the blocked forces for the free condition. The blocked forces are given by the following equation:

$$f_2^{bl,free} = \left(Y_{22}^{A}\right) + u_4^{free}$$

These forces can again be used to make a prediction u_{free}^{pred} to the validation points inside the car. These predictions can be compared to the measured signal and the predictions from the previous set of blocked forces. This procedure is called transfer validation and can prove the source independence of the blocked forces. The prediction is calculated similarly:

$$u_3^{pred,free} = Y_{32}^{AB} f_2^{bl,free}$$

The predictions were again validated at the driver's ear microphone and at the seat rail sensor. Fig. 8 shows the comparison between the measured signal and the prediction from the blocked forces obtained from the free condition and the mounted condition.

Both characterizations yield the same result. This means that the blocked forces are indeed independent of the testing conditions. This is even true for very different boundary conditions, meaning that the EC characterization is not affected by the mounting condition. It was also verified that the individual blocked forces show a high similarity between in-situ and freely suspended. This finding gives Volvo Cars and its suppliers the freedom to choose the most effective characterization method.

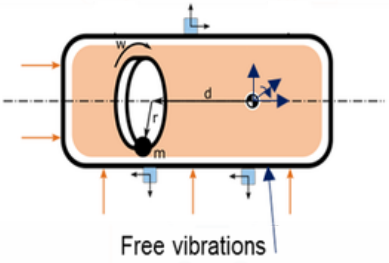


Figure 6: Schematic display of the EC freely suspended condition for In-Situ blocked force characterization.

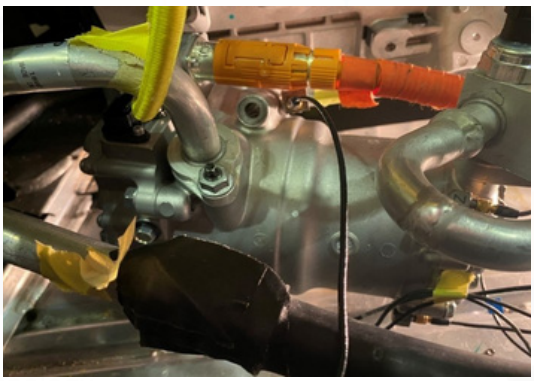


Figure 7: The freely suspended condition of the EC. One can see the compressor freely suspended with rubber ropes (yellow) in the engine compartment.

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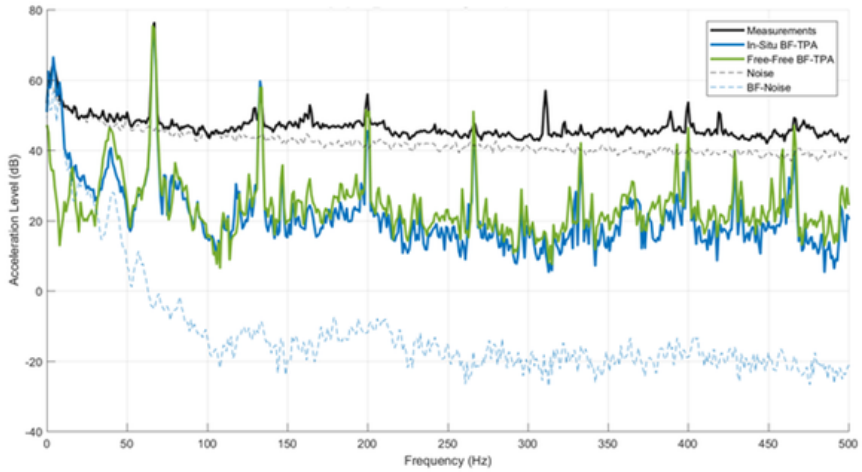


Figure 8: Comparison between the measured signal and the predictions from the blocked forces obtained from the freely suspended condition (green) and the mounted condition (blue).

NEXT STEP

One powerful way to further use the identified blocked forces is the combination with transfer paths obtained from dynamic substructuring (DS). DS can be used to simulate modular transfer path models. Together with the blocked force source description, new isolation/packaging concepts for the compressor can be studied for new platforms/vehicles. This allows the creation of virtual acoustic prototypes of assemblies that physically do not need to exist. Variants, for example, different bushing stiffnesses, can be virtually exchanged and evaluated. This saves development time and can avoid late-phase troubleshooting.

Definitions

In this project, the following notations are used:

- **ERC –** denoted with **A**
- **Receiver –** denoted with **B**

Furthermore, the following technical notations are used:

- $\mathbf{u}_3$ Response points;
- $\mathbf{u}_4$ Indicator points;
- $\mathbf{Y}_{42}^{A}$ FRFs of the ERC in free-free;
- $\mathbf{Y}_{42}^{AB}$ FRFs of the full vehicle, ERC CoG to the indicators
- $\mathbf{Y}_{32}^{AB}$ FRFs/NTFs of the full vehicle, from ERC CoG to the response points;
- $\mathbf{f}_2^{bl}$ Blocked forces/moments (6 DoF), in the CoG of the ERC.