Siemens Digital Industries Software

Accurately measure FRFs at high frequency

Leveraging Simcenter to meet the new challenges of electric and hybrid vehicles

Executive summary

Making informed decisions on acoustic target setting, sound package design, vibro-acoustic troubleshooting, etc., requires accurate data. In addition to realistic operational source data, you need precise frequency response functions (FRFs), the most comprehensive metric to describe the physical properties of a vehicle. Measuring vibro-acoustic FRFs is an art that has been applied and refined over decades. But with the shift to hybrid and electric vehicles, new challenges present themselves. Electric noise sources generate acoustic energy at a higher frequency than traditional combustion engines. In this white paper, we describe some practicalities of measuring high-frequency FRFs, unveil some potential challenges and demonstrate how using Simcenter™ Qsources™ hardware with Simcenter SCADAS™ hardware and Simcenter Testlab™ software can help you be successful. Simcenter products are part of the Xcelerator™ portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software.

Contents

Abstract

For decades structural and vibro-acoustic FRFs have been omnipresent throughout the vehicle development cycle as a useful source of information for various purposes. During the early design stages, FRFs can be used to help establish benchmarks to explore the market for what is currently a standard for performance, or to define system-level design specifications. Later on, FRFs can be used in analyses to fine-tune sound paths or for troubleshooting. They can also be useful for quality control during manufacturing.

Today, the transition from combustion engines to various sorts of hybrid and electric drivelines has increased the complexity of vibro-acoustic FRF measurements, as the bulk part of the acoustic energy content is in higher frequency bands. Typically, electromagnetic forces due to inverter switching lead to dominant noise at ear locations above 1 kilohertz (kHz). At these frequencies, it is challenging to inject enough energy into the system to obtain a response with a sufficient signal-to-noise ratio.

Still, having this FRF information is essential to understand these electric noise sources and evaluate what the role of sound packages can be in vehicles. Conducting numerical analysis by simulation is difficult in this frequency range, both because of modeling accuracy and computational requirements.

The following sections will provide you with some useful guidelines and essential information so you can accurately and efficiently measure vibro-acoustic FRFs. The importance of this cannot be underestimated as informed decisions can only be made when underpinned with precise data.

1 How to properly set up the measurement

1.1 Choosing the measurement locations

Even though exterior noise radiated from the vehicle can also be the subject of study, most of the time a setup includes a limited number of target locations inside a car, typically the ears of the driver and passenger(s).

On the other hand, at the source side the amount of locations can vary from one microphone per source up to 20 or more, depending on how much is known about the characteristic noise emission pattern of the source as well as the available time and resources.

Measurements are usually conducted in a semi-anechoic room, even though qualitative measurements can also be achieved in an open field or in a workshop environment as well. However, the external factors like wind-induced airflow and low damped reflections of workshop walls and ceiling must be taken into consideration.

In our study example, we consider the following measurement locations (see pictures below):

- Electric coolant pump front side
- Electric motor
- Power electronics module
- Front right passenger ear location

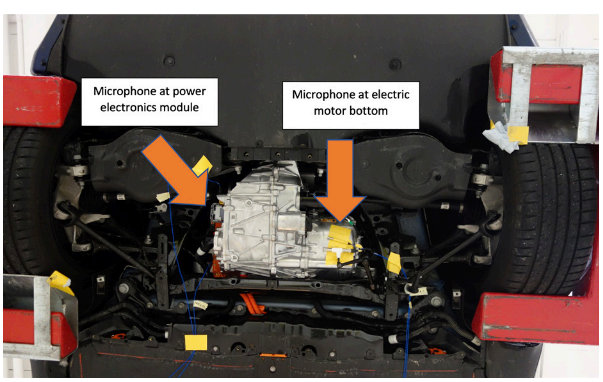


Figure 1. Rear side of the vehicle.

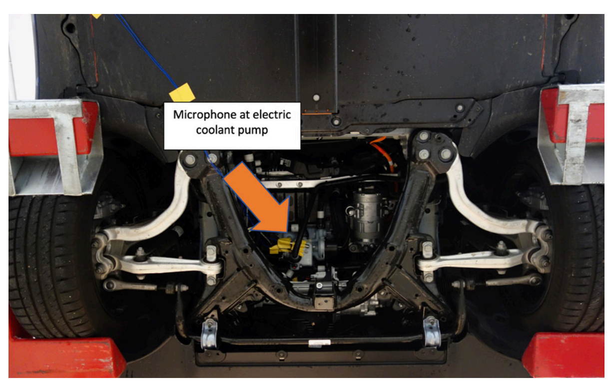


Figure 2. Front side of the vehicle.

The table below shows the typical values for measurement settings to be applied:

Specification	Value
Total tube length	2 meters
Bandwidth	25,600 Hz
Frequency resolution	3.125 Hz
Number of averages	50
FRF estimator	H1
Continuous random	Hanning/Hanning
Frequency range	Band limited 400 to 10,000 Hz
Type of signal	Random white noise
Simcenter SCADAS DAC Output voltage	5 V
Amplifier setting	+20 dB
Sound source strength	$6\ m^3/s^2$ RMS

Table 1. Typical measurement settings.

1.2 Direct versus reciprocal FRF measurement

Under certain conditions, the reciprocity principle holds: The test object should behave in a linear fashion in the considered frequency domain, the excitation should be time-stable (or stationary) and the sensors should match in terms of directivity. In that case, input and output of the system can be swapped and still lead to the same FRF.[1]

$$\left.\frac{p_3'}{\dot{Q}_4'}\right|_{\dot{Q}_3'=0} = \left.\frac{p_4^*}{\dot{Q}_3^*}\right|_{\dot{Q}_4^*=0}$$

Exploiting the reciprocity principle can save a considerable amount of testing time, especially when the number of targets is low and the number of sources high. On the other hand, direct excitation may yield a better signal-to-noise ratio as the microphones are then inside the cavity, more isolated from exterior, environmental disturbances. As a test engineer, you have to strike that balance.

1.3 The reference time signal at the right position

Whatever the setup, for further FRF estimation, reference signals of source strength sensors in the excitation devices need to be considered. In Simcenter QSources volume acceleration sources, those are integrated at the exit of the tube at the so-called nozzle. The spectrum in these locations is indeed different from the band-limited white noise that is (usually) defined as power density spectrum (PDS) in Simcenter Testlab. That's because of changes that occur during propagation through the tube.

During this process, pressure fluctuations inside the tube are so high the particle velocity is affected, making it a nonlinear acoustic cavity. As a result, sine waves that travel through the tube will increase in speed at maxima and decrease at minima. This alters the shape of the sine waves and generates shock waves, leading to a nonsymmetrical time signal. You can see this in the source strength time signal as sharper amplified positive pressure peaks and smoothed pressure lows (see figure 4).

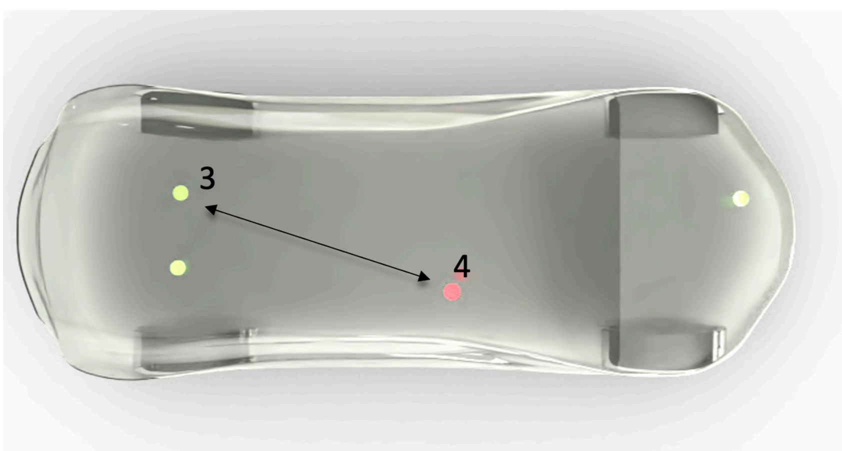


Figure 3. The reciprocity principle.

By having the reference sensor at the nozzle, it accurately captures internal resonances and wave effects, both linear and nonlinear, in the reference time signal. At high levels, internal source nonlinear effects can be significant as can be seen in the example. Beyond the sensor, for waves radiating outward from the nozzle, these effects usually become negligible.

An example autopower (power spectral density format) of the emitted noise captured by the reference sensor is shown below.

As you can see, standing waves impose minima and maxima on the output, and the nonlinear effect makes the spectrum continue to contain energy, even above the upper limit defined in Simcenter Testlab.

A resulting FRF dataset that can be used for analysis is shown in the figure below. The data shows in the third octave bands, as is common industry practice.

These FRFs allow you to compare acoustic isolation performance; for example, from different operational sources to the interior, between different sound package configurations or between various vehicles.

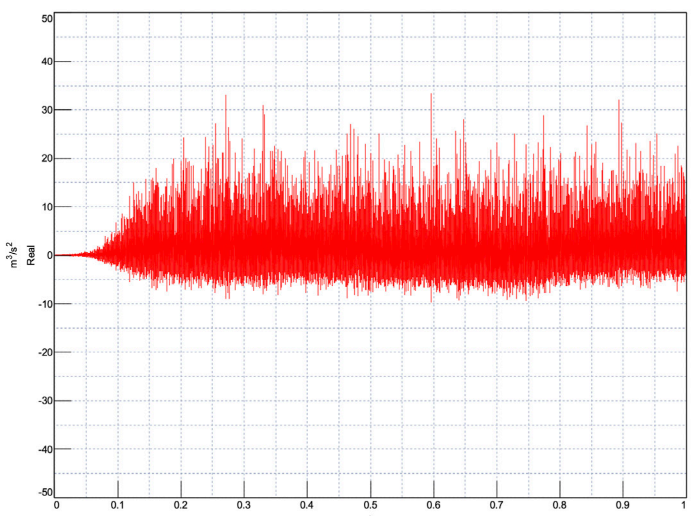


Figure 4. Time signal of the sound source strength sensor.

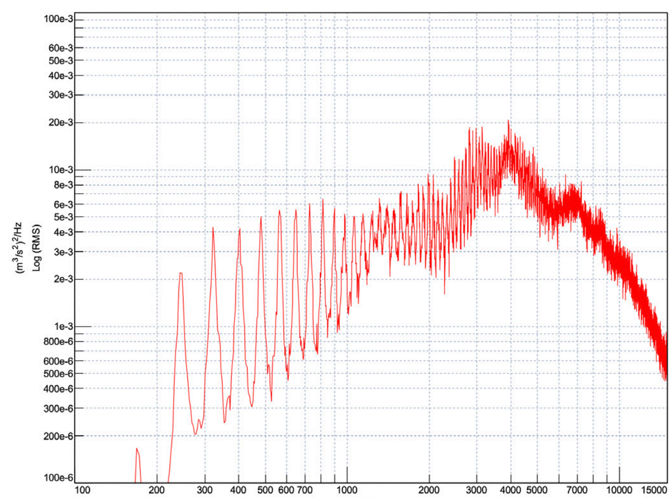


Figure 5. The autopower spectrum in PSD format of volume acceleration reference sensor with a 2-meter tube connected. The measurement amplifier was fed with a flat input signal.

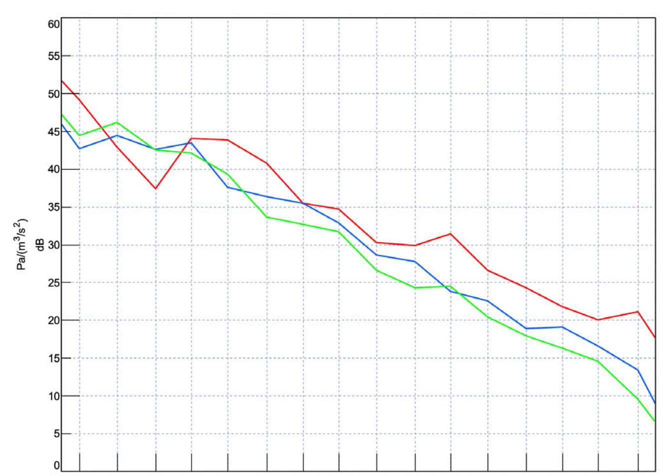


Figure 6. Acoustic FRF from three operational sound sources.

2 Measurement considerations

In the following paragraphs we'll discuss a few metrics for analyzing data quality as well as several elements that can influence data quality by means of some examples.

2.1 About background noise, coherence and repeatability

The signal-to-noise ratio is one of the major metrics to judge the quality of an FRF result. Many external sources can add to the total background noise, including microphone, source reference sensor, front-end and exterior environmental background noise.

In the following plots, you can see the microphone and the reference sensor autopower while the acoustic source is inactive (blue curves) and active (red curves).

A clear gap of multiple decibels (dBs) is visible when measuring on this vehicle across the trim.

The type of microphone that is used makes a difference here. In general, the larger the diaphragm, the better the microphone performs in terms of self-noise. That can be seen in figure 8.

In this display, the background noise levels of one-quarter-inch and once-half-inch are plotted against the level when the source is active. The smallest one-quarter-inch microphone (light blue) shows a higher background noise level.

The front-end background level was not isolated here. Its self-noise is not a critical factor in a typical FRF setup. The 24-bit digital-to-analog convertor (DAC) also mitigates the risk that quantization errors would become significant.

Together with the FRF estimation, the signal coherence should be measured as this gives a good indication of how much of the response is coming from the correlated source input (or inputs in case of multiple sources that operate simultaneously). Further, the repeatability should be verified to assess the quality and stability of the FRFs.

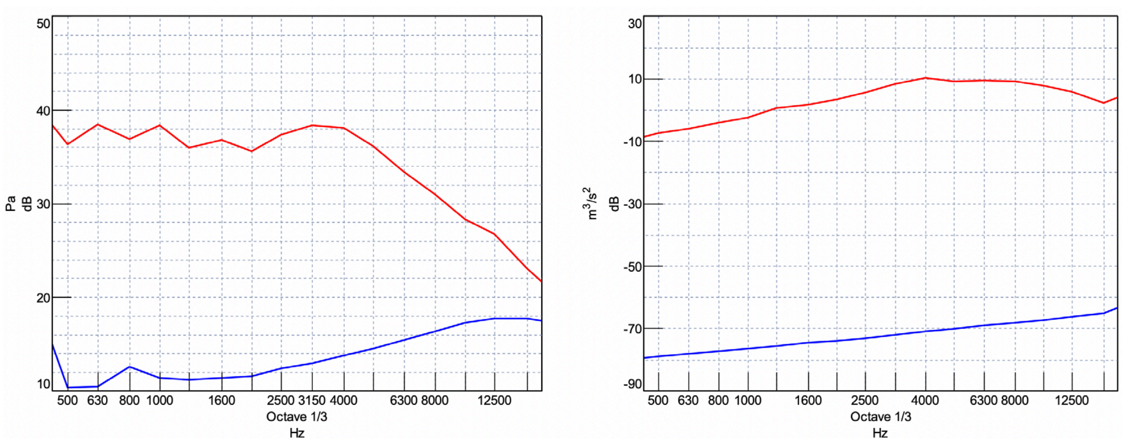


Figure 7. Left: microphone response spectra in PSD format, red: response during FRF measurement, blue: background noise, right: sound source reference sensor spectra, red: active, blue: inactive.

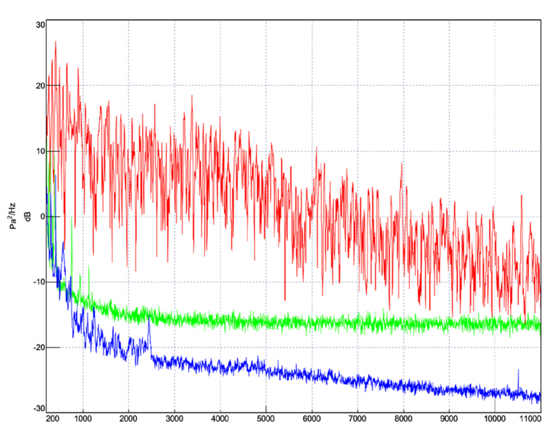


Figure 8. Microphone response spectra in PSD format, red: response during FRF measurement, blue: background noise one-half-inch microphone, light blue: background noise one-quarter-inch microphone.

The following diagram shows the FRFs of three operational sources:

The electric motor (blue), the power electronics (green) and the electric coolant pump (red).

In the narrowband display, you can see the overall coherence is around 90 percent with dips at discrete frequencies where the FRF also shows clear dips. The picture below contains a zoomed frequency axis explaining this.

When only a limited part of the frequency range is displayed, you can clearly see the minima in the coherence functions and those in the FRFs are tightly linked. That's because at these frequencies, the system response is low.

Still, coherence isn't everything and repeatability is a good quality indicator. As you can see below, even with a coherence below 90 percent almost perfectly identical FRFs can be measured, which is the ultimate goal of data acquisition.

The following three one-third octave band plots show two repetitions for each of the three locations:

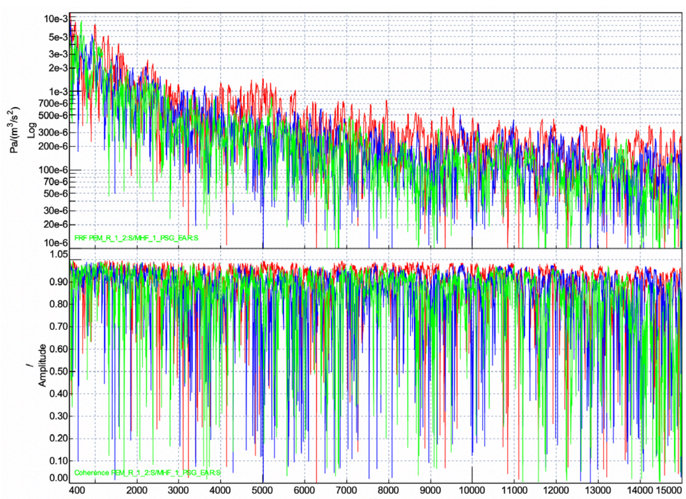


Figure 9. Upper diagram: FRF amplitude of three FRFs, lower diagram corresponding coherence function. Red: coolant pump, blue: electric motor, green: power electronics module.

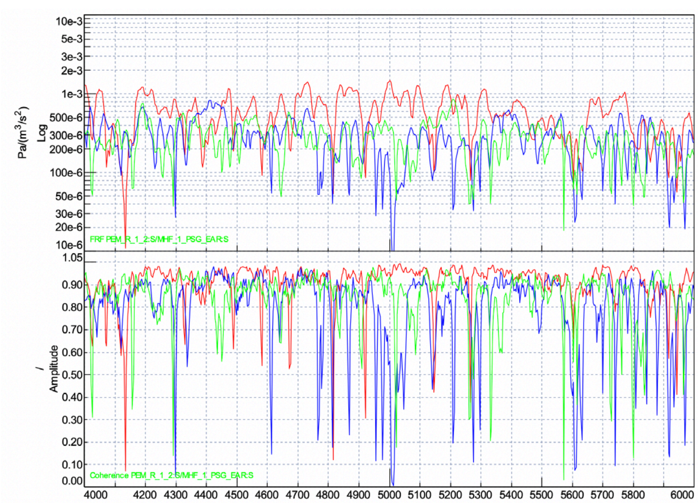


Figure 10. Zoomed in frequency: upper: FRF amplitude of three FRFs, lower coherence function. Red coolant pump, blue: electric motor, green: power electronics module.

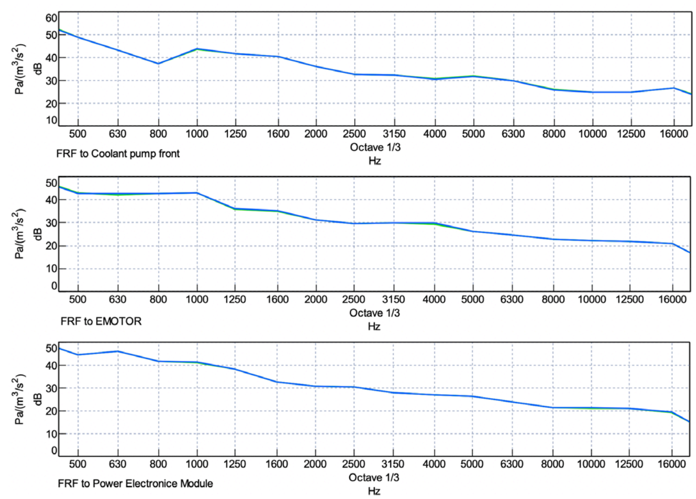


Figure 11. One-third octave plot of two FRFs measured for each point showing an exact copy of the result. Green: first FRF result, blue: FRF repeated.

2.2 Single input multiple output versus multiple input multiple output

As mentioned in section 2.2, a reciprocal measurement setup can dramatically lower the effort by decreasing the number of repositions. To further reduce the total testing time, you can also activate multiple sources at the same time. As long as the excitation signals are completely different and uncorrelated, the results can be decomposed in separate sets of FRFs.

The following Bode diagram shows a case for two FRFs.

One FRF has been measured when two sources were activated simultaneously. The second FRF (displayed in blue) has been acquired while only one source was active.

The narrowband spectra are nearly identical, thus proving the source signals do not interfere with each other. Below we show the same results in the more common one-third octave band format.

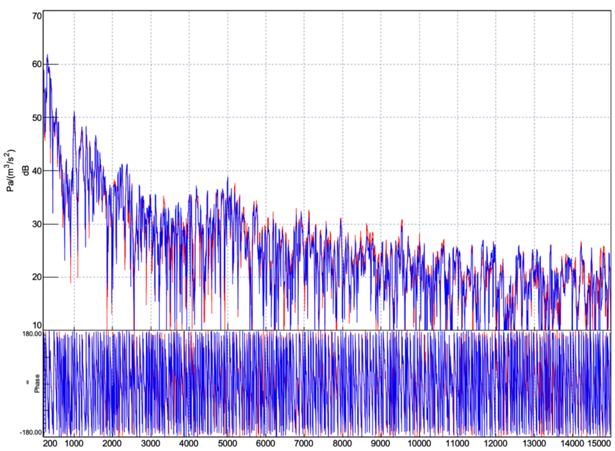


Figure 12. Comparison of FRF measured with one and two sources active, respectively. Blue: single source active. Red: two sources active.

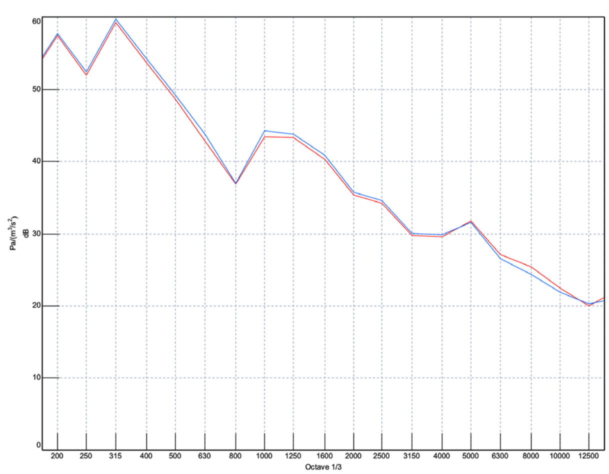
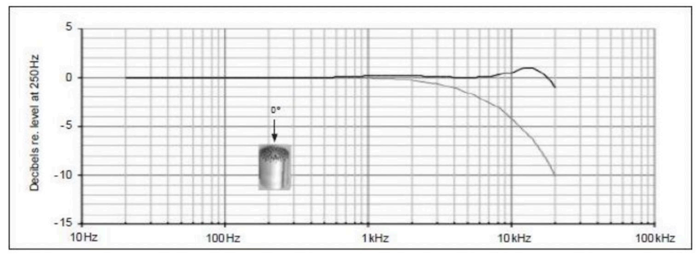


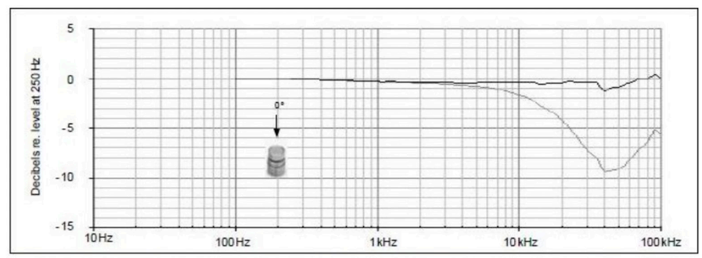
Figure 13. Amplitude in a one-third octave plot of an FRF measured with one source and two sources active, respectively.

2.3 Wavelength versus directivity of microphone and sources

Measuring higher frequencies also means measuring smaller wavelengths to the point the omnidirectionality of the measurement instruments may be affected. For one-half-inch microphones, this becomes a critical issue around 4kHz, whereas for one-quarter-inch microphones around 7kHz as illustrated in the pictures below.



Typical frequency response. Upper curve shows free-field response for 0°, lower curve shows pressure response.



Typical frequency response (without protection grid). Upper curve shows free-field response for 0°, lower curve shows pressure response.

Figure 14. Two directivity deviations for one-half inch microphone (top) and for one-quarter-inch microphone (bottom) (source: GRAS Sound & Vibration).

So the test engineer has to choose between the higher sensitivity of the larger diaphragms that come with one-half-inch microphones and the flatter high-frequency response that comes with the one-quarter-inch microphones.

A similar effect also manifests for the acoustic exciter, of which the orifice has a 9 millimeter (mm) diameter and the outer diameter at the noise emission is 13mm. This is visible from approximately 4kHz as well.

There is a measurement methodology that can be used to cancel these directivity effects.[2] The procedure is based on an averaging of two FRF measurements between which the source is rotated by 180 degrees. This also rotates the directivity. Averaging these two will cancel out this first level directivity. Note this will not work out anymore when you have multiple lobes in the very high frequency range. That is beyond the scope of this study.

The picture below shows a setup in which two sources are positioned in opposite direction. The FRF collection can then be done sequentially followed by the averaging.

The resulting octave diagram shows the two original FRFs in red and the average one in green. In this example, the amplitude variation between 5kHz and 16kHz is more than 1 dB in one-third octave band. The red hatched area represents the range in which the amplitude varies with the orientation of the source.

When zooming in on the frequency axis and looking in a narrow band, as in the picture below, we see even larger differences.

This effect unfortunately presents itself exactly in a relevant frequency range for electrified driveline development. So it needs to be taken into consideration during analysis. The energy-averaged FRF amplitude in green lies exactly in the middle. This one corresponds to a monopole excitation, which results in an equal excitation of all sound paths. The importance of sound package modifications is also not influenced by the FRF measurement setup.

Figure 15. Two sources positioned in opposite directions.

Figure 16. Upper: acoustic FRF between ear location and power electronics module. Red curves: single excitation. Green curve: energy averaged FRF of two orientations. Lower: the two opposed FRFs.

2.4 The influence of the distance between microphones and surface

Another aspect that can cause problems when measuring vibro-acoustic FRFs is related to the instrumentation of the source surface. When the microphones are positioned at specific distances from the surface, direct and reflected waves will interfere and potentially cancel each other out when they are in opposite phase. This can pollute the test and should either be avoided or corrected during analysis.

To illustrate this phenomenon, an FRF between ear and electric motor surface has been measured with a one-half-inch microphone at 2, 8, 20 and 40mm distance from the surface respectively. The position is shown in the sketch below. The one-third octave band FRF magnitude result for these distances are shown. The frequency at which the interference between direct and reflecting waves affects the FRF lower in frequency, as the microphone moves away from the surface.

In the plot you can see the different curves start to deviate from each other at a certain frequency. The curve that corresponds to the microphone at the longest distance is the first one to be affected. You can see the difference between the FRFs can become several dBs at higher frequencies; in this example, up to 5dB. If not corrected, this may result in a systematic underestimation of the energy transfer at higher frequencies. This example was with a one-half-inch microphone. But in the picture below, you can also see with the smaller one-quarter-inch microphones, we see a similar effect.

This example illustrates why it is highly recommended to specify the microphone position precisely when testing. When randomly positioned, the measurement uncertainty would be unacceptable.

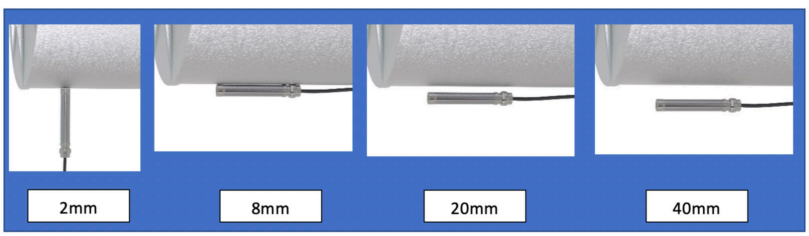


Figure 17. Arrangement of microphones.

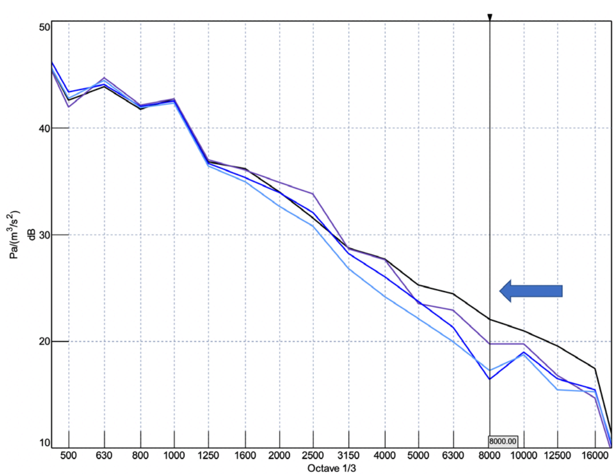


Figure 18. Amplitude of FRF with one-half-inch microphone at increasing distance from surface.

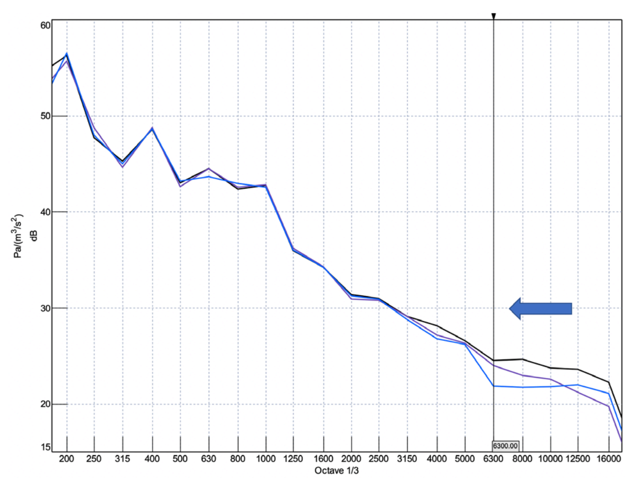


Figure 19. Amplitude of FRF with one-quarter-inch microphone at increasing distance from surface, 4 mm center to 20-mm.

2.5 Boosting noise output by reducing the frequency band

As explained in section 2.3, the nonlinear field inside the tube influences the wave propagation. This is no problem as this effect is captured by the reference sensor that is at the end of the nozzle. Even better, this nonlinear effect can be exploited to boost the noise emission at higher frequencies. By narrowing the excitation frequency range from, say, 200 to 15kHz to 500 to 5kHz, the shockwave phenomenon leads to even higher noise levels at high frequencies. This can result in several additional dBs above 5kHz, which can be a lifesaver for obtaining accurate and repeatable FRFs.

The following one-third octave plot shows the difference between a regular broadband spectrum and the concentrated power injection.

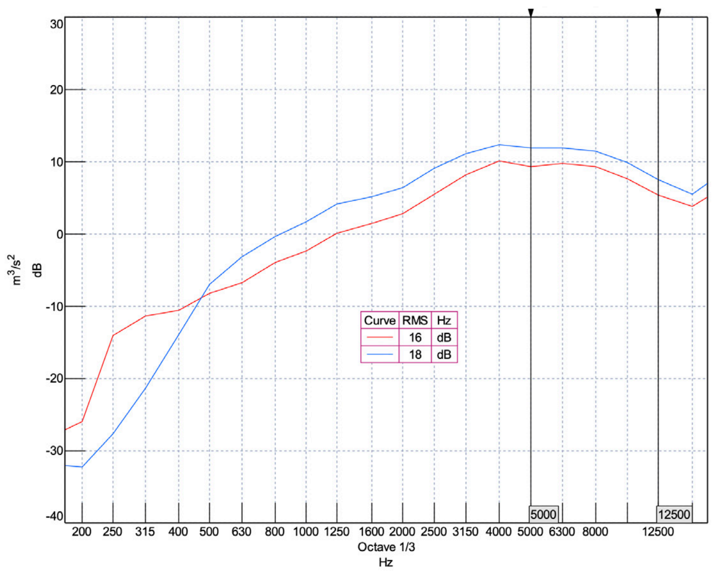


Figure 20. Autopower spectrum (PSD) of the volume acceleration. Blue curve: standard excitation signal. Green curve: concentrated energy 500-5kHz.

3 Protocol for successful high-frequency body isolation FRF measurements

The previous paragraphs described some practicalities about the measurement setup and some challenges that can occur. By means of examples, we showed that high-frequency FRF measurements are possible using Simcenter Qsources in combination with Simcenter SCADAS data acquisition hardware and Simcenter Testlab data analysis software.

Below we summarize the most important guidelines:

- Turn off nonessential machinery around the vehicle
- Ensure the vehicle is not producing any noise through its internal and external loudspeakers and cooling systems
- Stop any flow or even light draft in and around the vehicle
- Ensure the Simcenter SCADAS front-end has a 24-bit ADC and the input modules allow you to adjust the input range
- Use the 2-meter tube configuration to shift the acoustic energy toward the higher frequencies
- Consider using the opposite orientation excitation to minimize directivity effects
- Use one-quarter-inch microphones
- In case of free field microphones, correct the result to pressure response type microphones
- Place the microphone membrane center close to the test object surface, preferably within one-sixth of the wavelength corresponding to the highest frequency of interest; within 5.5 mm for 10 kHz, or within 3.5 mm for 16kHz
- Multiple simultaneous inputs reduce the total measurement time
- Consider electronic work instructions (EWI) to streamline the operating procedure between globally distributed teams

In case signal-to-noise ratio is insufficient:

- Analyze carefully to identify where high-frequency noises are coming from and limit these environmental noises where possible
- Use a band limited excitation from 500 to 5,000 Hz to achieve a higher level
- Consider direct FRF measurements in case of insufficient signal-to-noise ratio
- Consider investing in higher sensitivity microphones, different measurement environment

And finally, ensure all equipment meets all requirements of the calibration program. This is to reduce the risk on drifted sensors. Our calibration laboratory, located in Belgium, offers regular calibrations of the integrated sound source strength sensor.

The sketch below shows the connections between the different hardware.

Using the mid-high frequency source, it is recommended to set the high-pass filter on the amplifier to its maximum frequency.

Conclusion

Measuring accurate vibro-acoustic FRFs starts with a good measurement setup. To save instrumentation effort and time, you can make use of the reciprocity principle, but especially at higher frequencies that can impact the signal-to-noise ratio. An important part of the setup are the source strength reference sensors, as those will take all disturbances inside the source into consideration.

At high frequency, when it becomes difficult to inject sufficient acoustic energy into the system to obtain precise measurements, it is especially necessary to make sure background noises are eliminated. The choice of the microphone size also plays a role here. The data quality can be evaluated using coherence functions and by verifying repeatability.

Other specific challenges that can pop up at higher frequencies are the omnidirectional character of the measurement equipment can be affected and interference problems might occur when microphones are positioned at specific distances from surfaces.

The good news is we can also convert a weakness into a strength and turn certain nonlinear effects that appear inside the sound sources at higher frequencies into additional acoustic energy during FRF testing.

We also propose some guidelines that can help you accurately measure vibro-acoustic FRFs for hybrid and electric vehicles by combining Simcenter Qsources with Simcenter SCADAS and Simcenter Testlab.

References

1. Van der Linden, P.; Proost G.; Nijs, G., Siemens Industry Software NV, “On Efficient Reciprocal Measurement of Vehicle Body Airborne Isolation and Vibro-Acoustic Transfer Behavior,” Proceedings of ISMA2002 - Volume IV.

2. Knechten, T.; Coster, C.; Van der Linden, P., Siemens Industry Software NV, “Improved high frequency isolation and sound transfer measurements on vehicle bodies,” SAE paper 2014-01-2077.

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