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Siemens Digital Industries Software

Aero-acoustic wind tunnel testing for automotive

Enhancing the efficiency and effectiveness of testing for noise performance

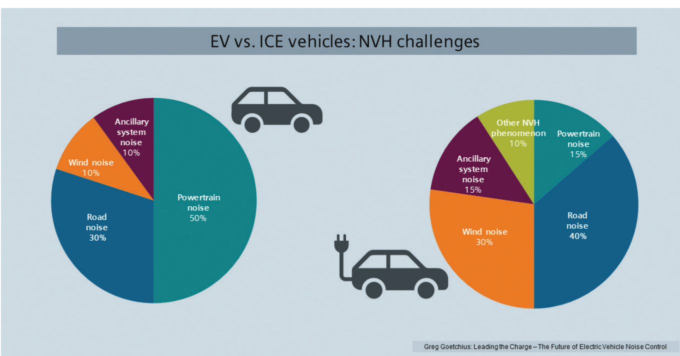
Executive summary

This white paper provides an overview and detailed discussion of different wind tunnel testing technologies, from basic to advanced, and describes Simcenter™ software testing solutions for efficient wind tunnel testing.

Contents

Abstract

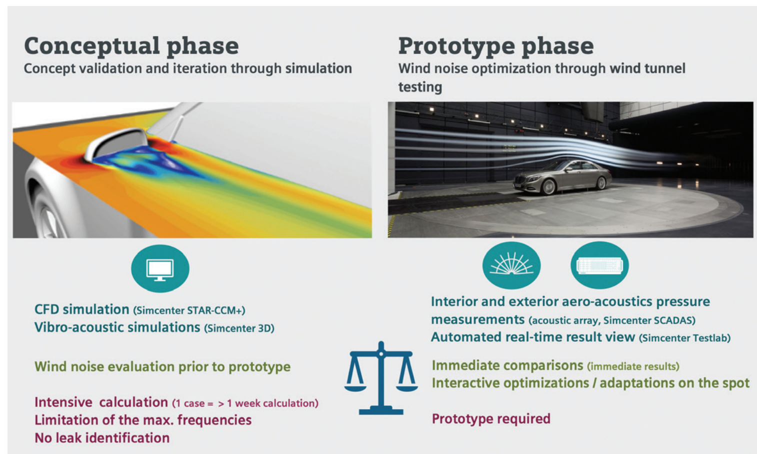
With the rising electrification trend in automotive industry, noise, vibration and harshness (NVH) development efforts of car manufacturers have shifted focus from powertrain noise to other sources, such as road and wind noise. Certainly, driving at high speed makes road and wind noise important. The fact this noise, which is not pleasant, is no longer masked by the combustion engine makes it important to reduce it. As early as 2011, it was clear that reducing aero-acoustic noise would become the second-highest priority for NVH teams after reducing road noise.



Shift in priorities in NVH development for electric vehicles.

There has been significant progress in aerodynamic and aero-acoustic simulation over the past years. You can get the most out of simulation when you use it at an early stage, enabling you to evaluate the consequences of certain design alternatives prior to having vehicle prototypes available. Also, understanding how flow-induced turbulence leads to exterior noise sources or how those combined with the vibro-acoustic characteristics of the vehicle can result in interior noise, can be assessed with simulation using Simcenter STAR-CCM+™ software and Simcenter 3D software. However, running full simulations requires intensive calculations (depending of the model and frequency, but it can easily take about one week) and has limitations in accuracy for mid to high frequencies. On top of that, a large part of the vehicle noise improvements come from improvements on seals and removal of leaks and weak spots that are hard, if not impossible, to simulate.

For this reason, once a prototype is available, wind tunnel testing is by far the most effective instrument for troubleshooting and improving the vehicle.



Wind noise engineering: Use simulation to build better first prototypes. Once prototypes are available, test inside the wind tunnel with maximum efficiency.

Why are wind tunnels needed?

Testing the vehicle while driving at high speed outdoors only allows you to measure the final vehicle noise target. This target will obviously be interfered with by other noise sources, such as road noise. Aero-acoustic wind tunnels offer great advantages: The wind noise can be isolated from other noise sources and they allow testing the vehicle under well-controlled conditions.

Wind tunnels also allow testing of the full energy flow of the wind noise generation process, from the aerodynamic source distribution generated around the vehicle to the transfer of these sources to inside at the driver's ear within the vehicle. This testing gives crucial insight into the full mechanism behind wind noise.

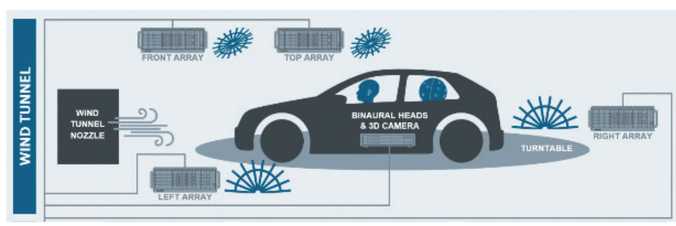
There is a lot of pressure in wind tunnel testing because there is an increased need to reduce wind noise for electric vehicles combined with the fact the most effective optimizations can only be achieved inside wind tunnels. Further, wind tunnels are expensive to construct and operate. As a result, the cost for one shift of eight hours easily exceeds €20,000.

For this reason, more than ever there is a need to boost testing efficiency in wind tunnels. Aero-acoustic engineers must capture as much information as possible during each test and need to have tools to allow them to focus as quickly as possible on the key issues. It is no longer sufficient to just measure the interior noise for different conditions, followed by lengthy one-by-one modification and comparing improvements step-by-step. It has become must-have information that provides insight into needed modifications.

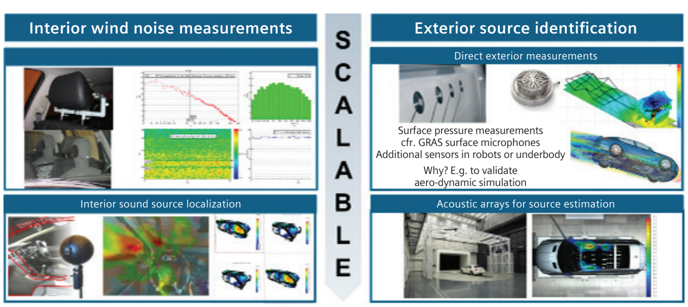
This white paper provides an overview of different measurement techniques that can be used in the wind tunnel, how they can be combined to gain more insight and how an efficient testing process can be implemented.

Overview of different wind tunnel measurement techniques

A combination of testing methods can help you get insight into the root cause behind high interior wind noise levels. To understand the full mechanism, it's important to have first methods that allow us to focus on the aerodynamic pressure generated by the flow outside of the vehicle and how those are translated into acoustic noise sources on the exterior. These are exterior measurement techniques. Secondly, other methods are used inside the vehicle and focus on noise levels and where they enter the vehicle.



Overview of where to position the different measurement technologies.



Overview of wind tunnel testing methods – combining exterior and interior methods to map the full flow.

Exterior noise: measuring source distribution around the vehicle

To gain insight into the aero-acoustic performance of the vehicle, it is important to understand the pressure distribution on the outside of the vehicle for different configurations.

Direct measurements within the flow

Directly measuring the local pressure within the wind flow aids understanding of exactly what happens within the wind flow. When a classical microphone is placed in a laminar flow, turbulence is created that in turn results in unwanted pressure variations on the diaphragm. There are a few adaptations required for microphones used for measuring flow.

By installing a nose cone on top of the microphone, the pressure variations caused by the turbulence starting at the stagnation point are moved as far away from the diaphragm as possible. Theoretically, this supports a longer-the-better design, but in practice it is a compromise between practical size and obtaining a streamlined shape of the cone.

The figure below shows an example of a noise cone. A design with a blunt tip was developed, forcing a predictable stagnation point at the tip. This turned out to be a great improvement compared to the classical design with a sharp tip. The surface is polished to a high gloss to improve aerodynamic performance.

GRAS nose cone for pressure measurements within a laminar flow.

The microphones can be directly connected to Simcenter SCADAS Mobile hardware in the vehicle, but it is often preferable to have the hardware outside since it allows of the user to prepare instrumentation before having the vehicle in the wind tunnel and avoids routing cables through the doors, which can cause new leaks and reduce aero-acoustic performance. For example, the additional hardware frame can be positioned and integrated below the turntable of the vehicle. This Simcenter SCADAS system, which is part of Xcelerator, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, can be easily combined with other Simcenter SCADAS systems by means of an optical master/slave cable.

Vehicle surface measurements by means of special microphones

The nose cone still requires the microphone to be positioned in the flow and it will impact this flow further downstream. For measuring the aerodynamic pressure on the vehicle surface with little impact on the vehicle flow, thin surface microphones can be used.

Use of surface microphones to measure sound pressure distribution outside the wind tunnel.

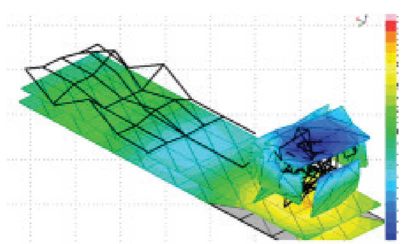
The picture opposite shows an example of surface microphones, which are mounted on the vehicle surface and measure the in-situ local pressure. Because the membrane is directly exposed to the wind flow, they measure the total pressure, which means not only the acoustic signals but also the local hydrodynamic component (local pressure phenomena that are not important for aero-acoustics). This is helpful for taking measurements for correlating with computational fluid dynamics (CFD) models. With special filter techniques, the aerodynamic pressure can be converted into aero-acoustic pressure.

As for aero-acoustics, the hydrodynamic pressure is not necessarily of interest. For this, an alternative is flush-mounted microphones. These microphones typically need to be integrated with components of the vehicle, such as windows, but offer the advantage they can attenuate the hydrodynamic pressure and only measure the aero-acoustic pressure. Obviously, it’s not easy to instrument them and requires drastic modifications to the vehicle being tested, which is a significant drawback.

A disadvantage of the surface microphones is they provide only local information and are quite time-consuming to instrument on the vehicle, but they are powerful for conducting detailed analysis of local phenomena.

GRAS flush-mount and flush-mount turbulence screen microphones for in-flow aero-acoustic measurements that attenuate the local hydrodynamic sound pressure.

Whatever microphones are used, they can be connected to Simcenter SCADAS, and data can be analyzed in more detail using Simcenter Testlab™ software. All acquired sound pressure levels can be visualized on the 3D geometry as well to gain insight into the location of the maximum pressure zones.



Visualization of pressure distribution on 3D geometry.

Derive sound pressure distribution on the outer surface of the vehicle

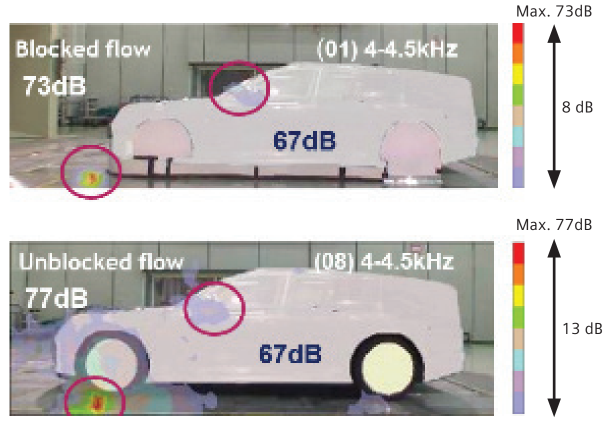
The aero-acoustic pressure distribution on the vehicle can be derived by means of acoustic arrays. These acoustic arrays consist of a set of microphones that are all connected to Simcenter SCADAS hardware and processed with beamforming (and other advanced algorithms), which allows deriving aero-acoustic pressure distribution on the vehicle.

Use of customized acoustic arrays for wind tunnel sound source localization. Example of one of the acoustic arrays.

Multiple arrays are usually preferred for focusing on all sides of the vehicle; left and right, on top and possibly in the front by placing an array on top of the nozzle pointing toward the front of the vehicle. It is important that all arrays are positioned outside the flow of the vehicle, which usually means the distance between the vehicle and arrays is several meters, resulting in large array sizes. Some of the arrays could have diameters up to 7 meters (m).

Acoustic arrays for wind tunnel application should be customized to optimize for:

- **Superior dynamic range:** The dynamic range is an important performance parameter for acoustic arrays. It quantifies the ability to localize a source that is an unknown number of decibels (dB) lower in level than the maximum sound source. A dynamic range of 13dB over the frequency range of interest is a minimum requirement for this application and is often further optimized for certain frequency ranges. The figure below illustrates the importance of having a dynamic range that is sufficiently large: The sound pressure distribution of interest around the side mirror would be masked by the maximum sound pressure around the front tire if the dynamic range is lower than 13dB



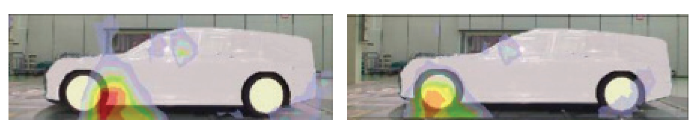
You need a dynamic range of at least 13dB to be able to capture all sources of interest.

- **Superior spatial resolution:** The ability to separate two sound sources is defined as the width of the main sound source at -3dB. The spatial resolution should be as high as possible. Very common spatial resolution would be around 1.2 * Lambda (wavelength of sound)

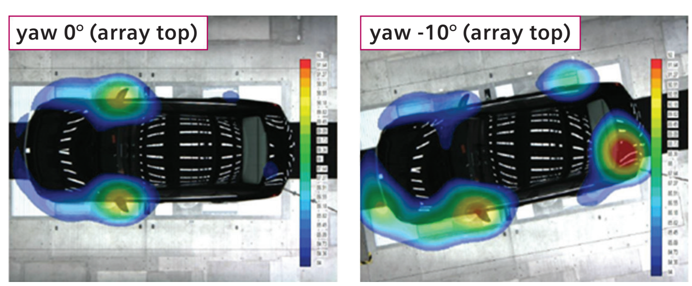
Certain processing functionality for wind tunnel applications are important assets:

- **Wind speed and yaw angle correction.** Due to the wind speed, the localized sound sources are shifted downstream. The wind speed correction functionality takes into account the shear layer refraction for a number under Mach 3. The figure below shows a comparison of the results without and with wind speed correction. Similarly, yaw angle corrections are applied to compensate for the angular rotation of the vehicle with respect to the flow. These corrections are applied automatically by using the wind speed coming from the wind tunnel controller.

Without correction (200 km/h) **With correction (200 km/h)**

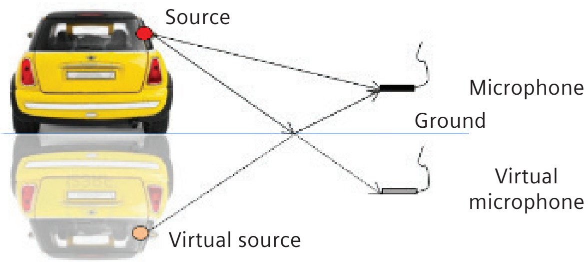


Automatic compensation for wind speed.



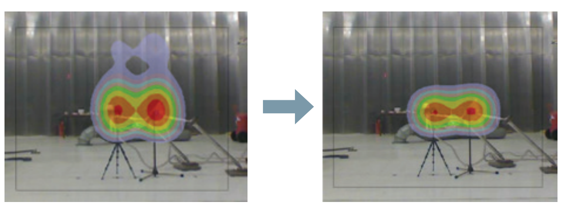
Yaw angle corrections – calculation grid automatically rotates with the yaw.

- **Doubling of spatial resolution for vertical acoustic arrays.** A specialized algorithm makes use of the reflections of the sound sources on the ground of the wind tunnel. In principle the algorithm doubles the size of the acoustic array in the vertical direction by adding virtual microphones as shown in the figure below.



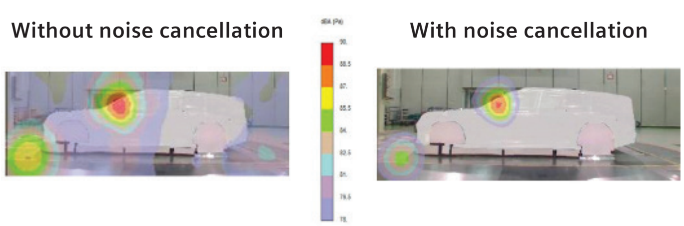
Doubling the size of the vertical arrays to double spatial resolution.

The result of this processing is the spatial resolution is doubled in the vertical direction with the same number of microphones as shown in the figure below.



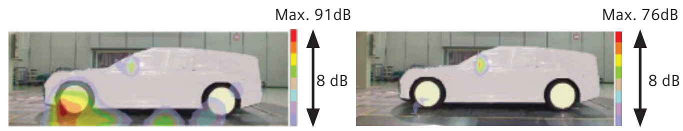
Increased vertical spatial resolution thanks to an algorithm using ground reflections.

- **Wind noise cancellation algorithm.** Although the microphones are positioned outside the main wind flow, they still suffer from a greatly reduced signal-to-noise ratio. Simcenter provides special processing to remove the noise component from the measurement. The wind noise cancellation processing allows an increase in spatial resolution.



Wind noise cancellation algorithm increases dynamic range by removing artificial sources.

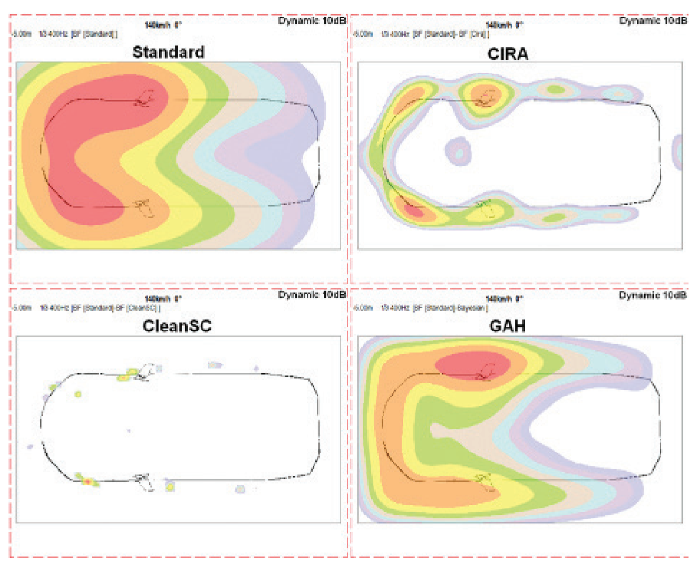
- **Coherence-based processing.** Not all sound sources generated around the vehicle are important for the noise inside the vehicle. Coherence-based processing is key to understanding which sources contribute most to the sound within the vehicle. This processing allows you to calculate sound sources that are coherent with noise measured within the vehicle; for example, with a binaural head.



Note: 1,600 Hz third octave band - config 08 140km/h

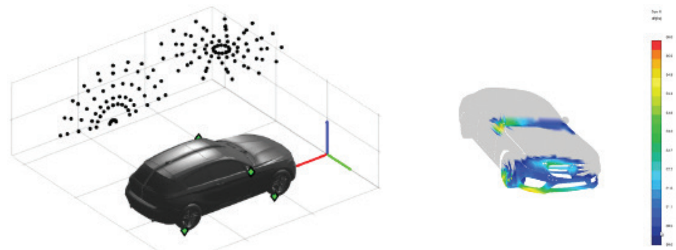
Without (left) and with (right) coherence processing. Coherence processing shows that turbulence at the side mirror of the vehicle is much more important for the noise in the vehicle than the turbulence on the wheel.

- **Additional processing.** To further improve the spatial resolution and dynamic range from the initial sound source localization results, additional processing methods are important. These are crucial to improve the spatial accuracy, which is certainly the case for low frequencies. Different complementary methods are available, including CIRA, CLEAN-SC and generalized acoustic holography (*Microphone Array Deconvolution Methods for Efficient Aeroacoustic Testing in Wind Tunnels, Inter.noise 2019*). The visual below shows a comparison of the different techniques for 400 hertz (Hz) 1/3 octave band. Please note the important improvements to spatial accuracy.



Comparison of additional processing techniques with respect to beamforming at 400 Hz.

- **Propagation on the 3D geometry.** If a computer-aided design (CAD) model of the vehicle is available, results can be obtained by propagating the results on the 3D geometry of the vehicle instead of a plane. This allows you to further improve the localization results and dynamic range.



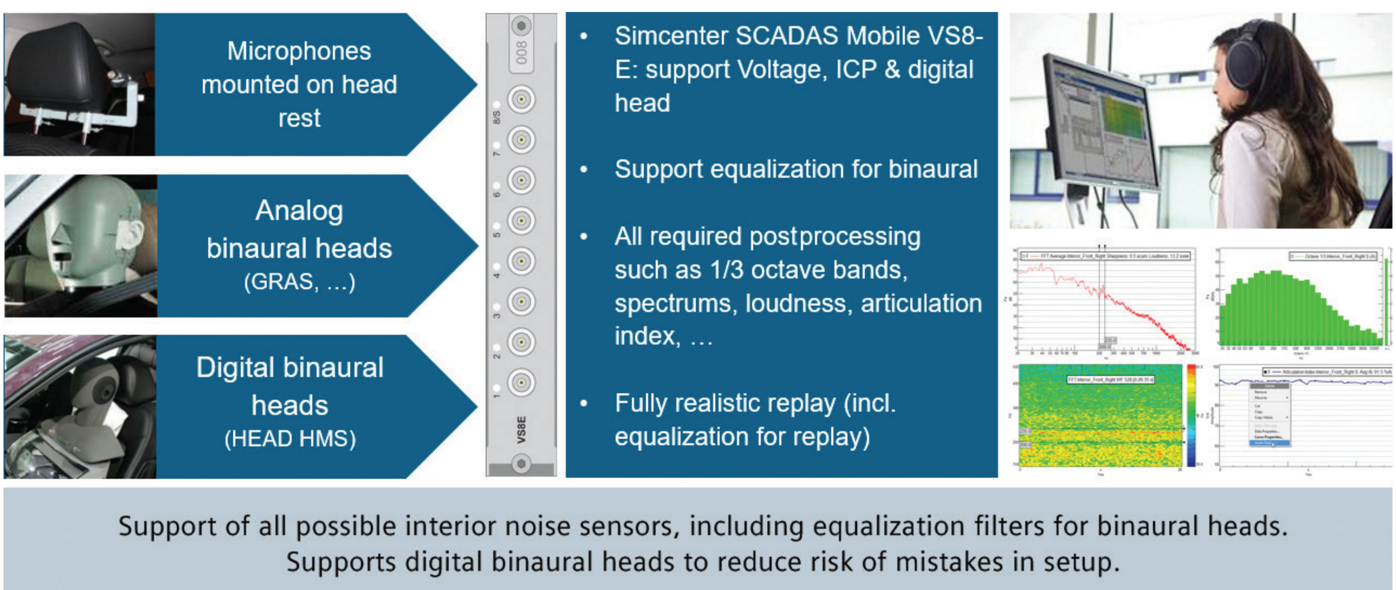
Using the 3D geometric information of the vehicle (CAD model) to propagate results.

Interior aero-acoustic noise measurements

Noise recording inside the vehicle

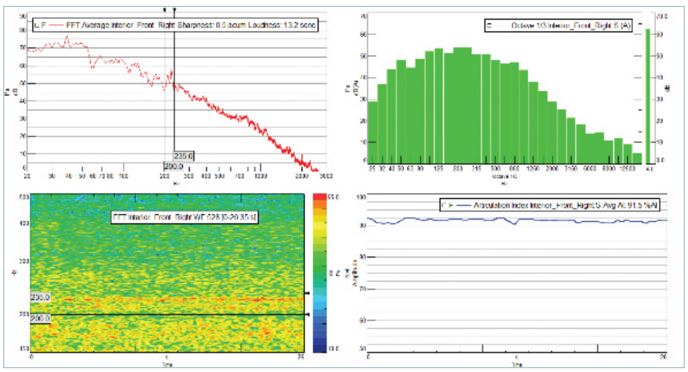
It is required to have the capability to record in-vehicle acoustic noise levels for different vehicle configurations (varying wind speed, yaw angles or modified vehicle configurations). Most often the sound is recorded at ear positions, potentially by using binaural heads.

To avoid spending costly wind tunnel testing time on the instrumentation of the vehicle, this should be prepared prior to placing the vehicle in the wind tunnel and consuming expensive measurement time. This can be done by connecting all in-vehicle instrumentation to Simcenter SCADAS Mobile hardware in the vehicle.



Shown is the sound quality measurement process. Simcenter SCADAS hardware supports all types of sound quality data acquisition, such as single microphones and digital binaural heads. Realistic replay of acquired data is fully supported.

Any type and number of microphones, analog or digital binaural heads, can be connected to Simcenter SCADAS Mobile hardware VS8. Recorded signals can be viewed in frequency, octave bands or overall levels, but also as sound quality metrics, including loudness and articulation indexes. All data can also be replayed during or after measurement (including binaural replay). By comparing recorded data and replaying data for configurations, engineers can obtain insights into the aero-acoustic performance of the vehicle.



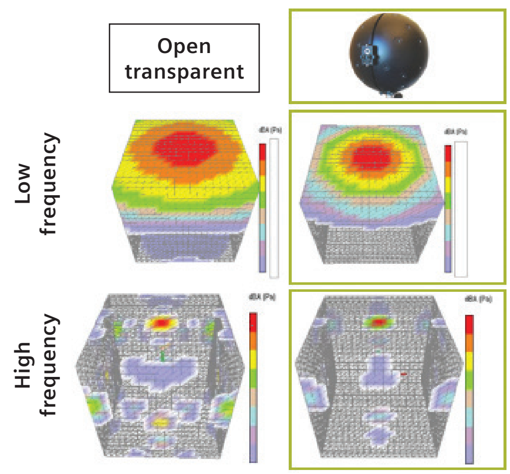
Using Simcenter Testlab as an example of aero-acoustic sound quality processing. All relevant sound quality metrics are fully supported.

Interior sound source localization: where does the sound enter the vehicle?

Recording the sound pressure levels in the vehicle allows comparison of different vehicle configurations but does not provide real insight into why certain vehicle configurations are good or bad. Simcenter Testlab 3D Acoustic Camera provides that information, identifying areas within the vehicle that contribute to the noise. Typical examples are leaks in seals of doors and windows, or vibration of full panels such as windows or roofs. The results can be displayed for different frequency bands. The Simcenter Testlab 3D Acoustic Camera used for the wind tunnel application consists of 54 microphones positioned on a solid sphere that are connected to Simcenter SCADAS hardware.

The Simcenter 3D Acoustic Camera can be used to localize the sources from within the cabin. Its design includes crucial specific elements to provide best-in-class performance in real in-vehicle circumstances:

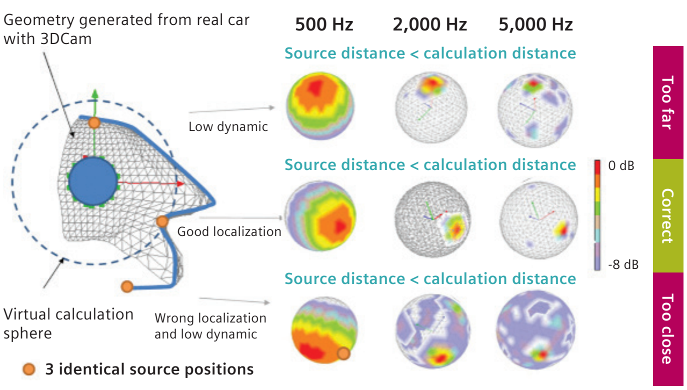
- **The use of a solid sphere instead of open sphere microphones:** Data processing takes into account the diffraction around the solid sphere (instead of an open sphere), making use of a spherical beamforming technique. This improves the spatial resolution (the accuracy of localizing the various acoustic sources) and the dynamic range (the ability to identify sound sources that are below the level of the maximum sound source). Having a high dynamic range is important for capturing not only the most important noise source, but also secondary contributors to the wind noise that may become dominant as the primary sources are reduced through the aero-acoustic development process. A dynamic range of at least 12dB for low frequencies (up to 1 kilohertz (kHz)) and 8dB for higher frequencies is critical and can only be reached in non-free-field circumstances when using a solid sphere. The solid sphere's effect on dynamic range becomes apparent only in real circumstances, where its official specifications remain true



Comparison between open and closed sphere (real source located on top). Improved spatial accuracy but lower ghost images, which means higher dynamic range for high frequencies.

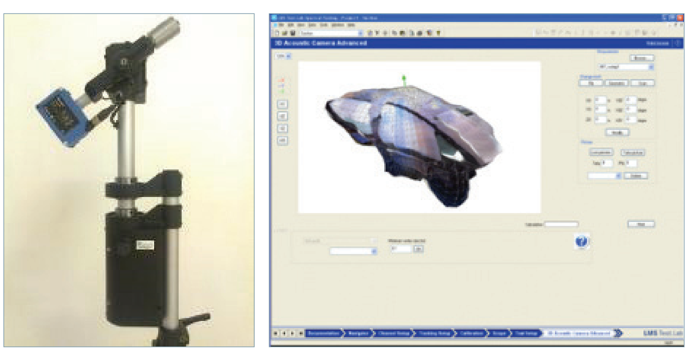
- **Projection onto 3D mesh geometry.** Typical beamforming approaches assume that sound sources are present at a fixed distance from the microphone array, either on a plane or a spherical surface with a fixed radius from the center of a spherical array. In order to obtain accurate results, it is important to identify the sources on their exact location; that is, the 3D mesh of the cavity rather than an assumed spherical surface. The errors that occur when projecting onto a spherical surface instead of the 3D mesh of the vehicle are shown in the figure below. Projection onto a sphere leads to a reduction in dynamic range with the creation of artificial side lobes and erroneous localization for lower frequencies

Distance calculation influence



Error generated by propagation toward a simplified sphere instead of 3D mesh from cabin. It is crucial to locate sources on the physical interior mesh of the vehicle.

A mesh is required to identify the exact location of sound sources. An existing CAD mesh of the interior of the cavity can be used, or in most cases the 3D mesh is acquired through the Simcenter 3D Photo Geometry scanner.

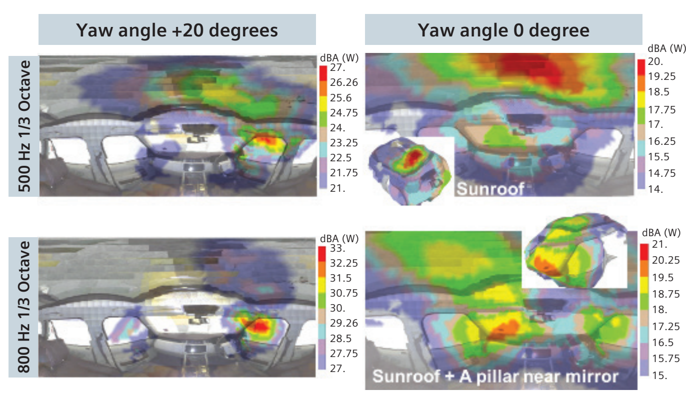


The Simcenter 3D Photo Geometry scanner provides accurate geometry of the vehicle.

Result of geometry scan from the Simcenter 3D Photo Geometry scanner.

The acquired geometry can be shown in 3D, but it is often preferable to view the mesh in an unwrapped view. Although this view shows the top and bottom highly deformed, it offers the advantage of viewing the entire vehicle at once.

Once the scan of the vehicle is made, as many vehicle configurations as required can be measured. For each configuration (duration, 10 to 20 seconds), the results can be viewed in different frequency bands. Shown below are examples of some typical results.



Simcenter 3D Acoustic Camera results for an SUV in a wind tunnel at wind speeds of 160 km/h for different yaw angles. The sunroof (top) contributes to the noise and at a positive yaw angle of +20 degrees so does the top of the seal of the right door. The wiper location also creates a noise source on the windshield at 0 degrees yaw angle.

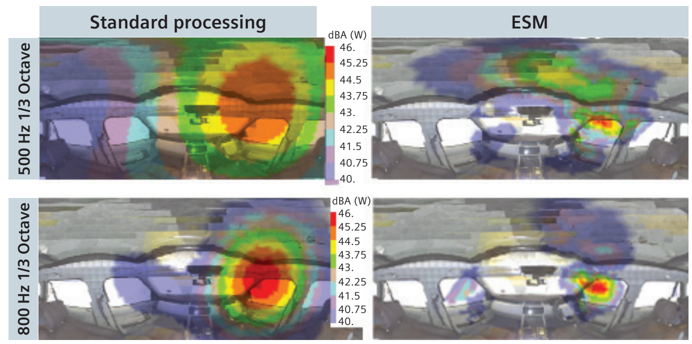
Simcenter wind tunnel testing solutions provide an additional method for sound localization for calculating a monopole source distribution onto the 3D mesh. The algorithm, known as equivalent source modeling (ESM), is an inverse method. It solves for a monopole source distribution that provides pressure distribution along the sphere equal to its measured sound pressure.

Although ESM requires some additional calculation, it offers clear advantages compared to classical spherical beamforming:

- **Improvement of the spatial resolution.** ESM is particularly valuable at frequencies below 1kHz when classical beamforming may not provide sufficient spatial resolution. A typical example is shown in the figure below
- **Quantitative results.** As ESM calculates a monopole source distribution, radiated sound power along a certain area of the mesh can be calculated. These quantitative results allow sound source ranking between areas of the mesh and one-to-one comparisons between the different measured configurations

As ESM is an iterative calculation that starts from the results obtained with spherical beamforming, the beamforming results must be as accurate as possible. For ESM processing, the use of the solid sphere and propagation on 3D geometry is crucial.

As ESM assumes a source distribution consisting of uncorrelated noise sources (a relevant assumption for wind noise), it is valuable for wind tunnel measurements.



Comparison of classical spherical beamforming versus ESM for low frequencies. ESM significantly increases the spatial resolution for low frequencies.

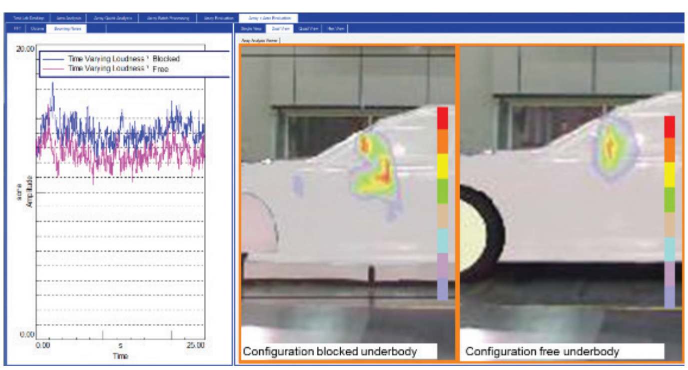
From measurement to engineering insight

Integrating measurements into one database

All of the testing solutions discussed in this document have their value and help the user gain insight into root causes of wind noise problems. These techniques are increasingly combined in an integrated data set.

Combining all measurements offers many advantages:

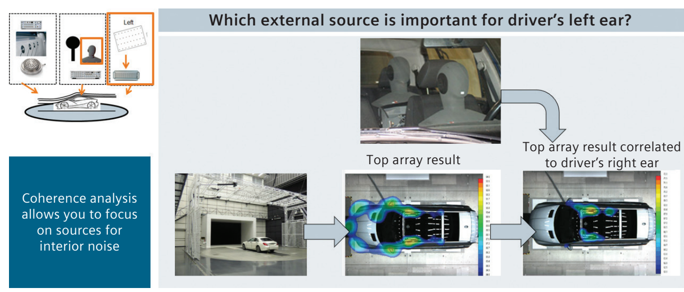
- All measurements start together automatically. Further, it is becoming common practice to integrate the acoustic system with the wind tunnel controller so you can exchange information such as vehicle parameters. It also enables you to make tests run automatically and automatically store the wind tunnel operational conditions (wind speed and yaw angle) in the acoustic test
- Test documentation and wind tunnel operational parameters only need to be stored once and are used in data selection and processing
- *Results from different systems can be more easily compared and synchronized and data can be more easily exchanged*. For instance, the Simcenter aero-acoustic solution enables engineers to show the relation between a certain sound quality metric and pressure distribution from an array



Linking sound quality and array results (array results here are shown for top array with artificial source). Viewing these results together allows understanding of the link between pressure distribution on the vehicle and the loudness measured within the vehicle.

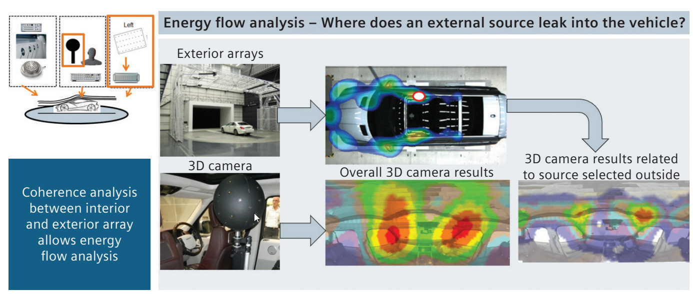
- *The full energy flow is measured* from source generation outside the vehicle to final noise at the driver's ear. Results from one technology can be used in another. For example, binaural head data can be used for coherence processing of the acoustic arrays. The Simcenter Testlab 3D Acoustic Camera results can be used for coherence analysis with exterior acoustic arrays or coherence processing with sound pressure measured outside with surface microphones.

  The example below shows results measured with a top array without (left) and with (right) reference to the sound recorded at driver's right ear.



Example of pressure distribution without and with correlation to interior microphone at driver's ear.

Also, coherence between exterior and interior array results can be calculated similarly, as shown in the next example.



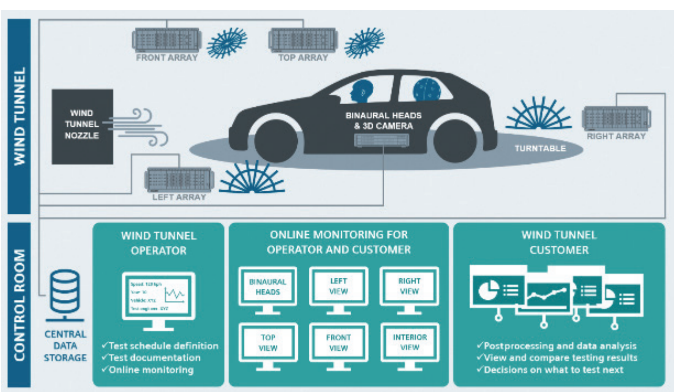
Identify where an exterior acoustic source leaks into the vehicle by doing coherence analysis between different array results; coherence analysis between interior array and a grid point from exterior top array results.

From integrated testing solution to industrial process

As indicated in the executive summary of this paper, wind tunnel testing is costly and there is usually little wind tunnel testing time available. It's crucial to get the maximum out of a test campaign. It is key to be able to pinpoint the root causes of the wind noise problems during the test and use the results to assess the impact of modifications during the same campaign. In theory, the different testing technologies discussed earlier can all help to achieve this: Exterior arrays provide insight into the exterior sources, interior arrays on where they enter the vehicle and interior microphones and their analysis provide insight into quality aspects of the sound.

However, the critical success factor is those test results are immediately available after each measurement and can be easily compared with previous test results; for example, before applying a modification. This requires an industrialized measurement process, as shown in the figure below.

For this reason, it is crucial to be able to analyze and view all the results from the different measurement techniques as quickly as possible.



Industrialized Integrated wind tunnel testing configuration focused on efficiency.

Key highlights of this implementation are:

- **Streamlined data**
  All measurement systems are measured together in full synchronization and saved on a central data storage unit
- **Efficient setup and instrumentation**
  The setup of the acoustic arrays and instrumentation of the vehicle should be as efficient as possible; for example, data acquisition hardware can be permanently installed on the arrays. Total setup time from scratch should be as short as possible – for instance, 10 minutes – in order not to lose valuable wind tunnel time
- **Automated measurements**
  Measurements run automatically by implementing integration between the acoustic test system and the wind tunnel controller. In this case, previously defined test schedules can run automatically
- **Immediate and interactive result view**
  Different parties are involved in the test, including the operators, wind tunnel customers or acoustic experts. It is crucial to determine how these people should work together and who gets what information in the wind tunnel control room.

Customized solution to provide all stakeholders what they need when they need it

On one hand, customized interfaces and systems for the wind tunnel operator are helpful. It allows the operator to select test schedules, monitor the test and document it with all required attributes and information. All specified wind tunnel operating conditions, vehicle parameters and vehicle conditions are automatically stored in the wind tunnel project. This doesn't only speed up test procedures, but it reduces the risk of human error when annotating wind speed and yaw angle.

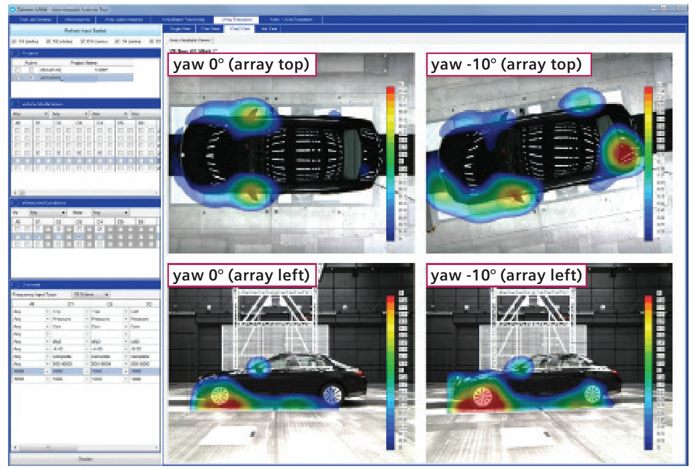
The wind tunnel customer and acoustic expert has one or more systems for analyzing and viewing the test results during the operation. More interestingly, all test results can be interpreted and compared with previous measurements in a user-friendly interactive view. The engineers can now focus on the test rather than on the setup. This system is the key piece of the advanced solution, as results rapidly become available after a measurement. It is here the crucial time-saving decisions are taken on what conditions or modifications to test next. Consequently, the teams are now able to test more vehicle design variants in one campaign, or simply to reduce the time required for the particular campaign. Finally, all stakeholders can benefit from real-time view on separate screens (one per array) to detect problematic situations during operation of the wind tunnel.

- The customer system used by the expert is the core building block that is used to analyze during the test and make decisions of what to test next. The entire process needs to be optimized from measurement to results:
  - It should be possible to automatically execute processing. Also, manually started processing should

be available, but in an easy way to allow batch processing

- Calculation speeds for the array data should be fast to supply fully processed results in seconds rather than minutes
- Processed results should be easily accessible and available on one screen for comparison. In the end most insight is obtained by being able to compare the difference between frequencies, arrays, wind speeds and yaw angles or different modifications. The flexibility of what to compare should be made available in an as simple way as possible. The figure below shows a comparison between a 0 and -10-degree yaw angle. This comparison is obtained with only few clicks

140 kph – 3rd octave – 1 kHz



Efficient comparison between two different yaw angles.

Conclusion

As new electrified vehicles increase the importance of aero-acoustic noise, more wind tunnel testing is required. As these tests are expensive and the time of the prototype is limited, there is extremely high demand and pressure to achieve maximum efficiency for each testing campaign. It is crucial to capture the maximum amount of information from acquired data and use this information to test the right things.

Combining different aero-acoustic testing technologies within one system is of great benefit and provides new insights for improving vehicle aero-acoustic performance. To truly achieve the objective of enhancing wind tunnel efficiency, this paper explains there are three main priorities: Use advanced measurement technologies to visualize the acoustics sources outside and inside the vehicle, measure all data together in one integrated data set and implement the process so it provides the test results immediately after a test to the right stakeholder. Only then can this stakeholder make the right decision on what to test next.

Siemens Digital Industries Software

Headquarters
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 972 987 3000

Americas
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 314 264 8499

Europe
Stephenson House
Sir William Siemens Square
Frimley, Camberley
Surrey, GU16 8QD
+44 (0) 1276 413200

Asia-Pacific
Unit 901-902, 9/F
Tower B, Manulife Financial Centre
223-231 Wai Yip Street, Kwun Tong
Kowloon, Hong Kong
+852 2230 3333

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