# Aero-Vibro-Acoustics For Wind Noise Applications

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## Introduction

Wind noise is high on automotive customers' minds when they judge the quality of a vehicle. In the J.D. Power 2014 U.S. Vehicle Dependability Study [1], excessive wind noise is listed as no. 1 amongst the top 10 problems most commonly experienced by vehicle owners. Whereas automobile manufacturer have a good handle on optimizing aerodynamics for minimizing drag force, reducing wind noise has remained a stiff challenge. Wind noise comprises three advanced physical problems, making it more complicated to simulate and predict. As a result, until now automakers have had to rely heavily on costly and time-consuming wind tunnel testing for wind noise reduction. A new simulation method - Deterministic Aero-Vibro-Acoustics - has now been developed to solve all the three physical problems involved in wind noise as a single set. This method is based on first principles not requiring statistical or empirical techniques such as transfer functions, and can be used by engineers to predict wind noise with accuracy and confidence.

## Challenges

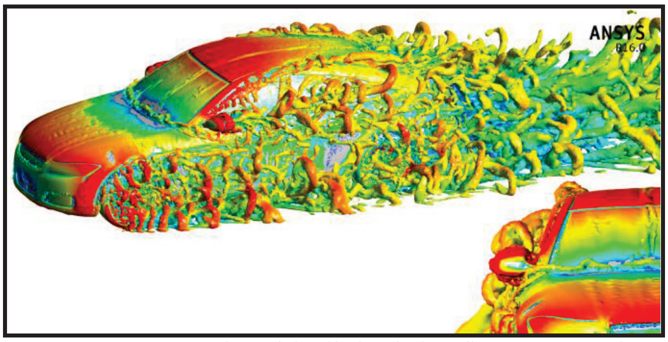
Wind noise is a physical problem that involves the three complicated aspects each governed by a different physics:

- Sound generation: governed by fluid dynamics
- Sound transmission: determined by structural mechanics
- Sound propagation: governed by acoustics

**Sound generation:** Wind noise is generated on the vehicle's outer surface due to turbulence in the surrounding air flow. Obstructions such as the A-pillar, side view mirror, and wipers disrupt the air flowing past the car and produce intense turbulence. Picture 1 shows the iso-surface of the Q-criterion (a characteristic quantity of the turbulence field) with detailed turbulent flow structures generating wind noise. As turbulent eddies move past or impinge on flat surfaces, they create pressure fluctuations on the side window, windshield and other body panels. These pressure fluctuations are the source of wind noise and are governed by the fluid dynamics of the air flow.

**Sound transmission:** The pressure fluctuations acting on the vehicle body's outer surface create minute vibrations transmitted through the thickness of the body panels, glass and trim and reach inside the cabin. These vibrations and their transmission are determined by structural mechanics of the body structure.

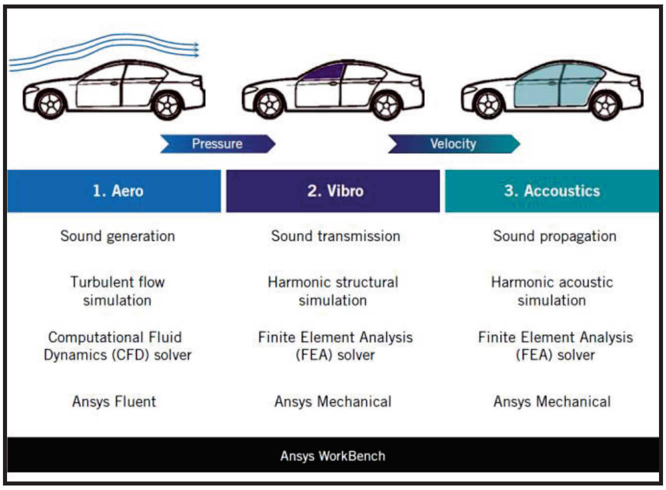
**Sound propagation:** The vibrations that reach the vehicle body's inner surface excite the air in the passenger cabin and propagate as sound waves from the inner body structure to the driver's ears. This propagation is governed by acoustics of the cabin air cavity. Whereas aerodynamic drag force is only related to fluid dynamics, wind noise comprises of these three advanced physical problems, and has been much more complicated to simulate and predict. As a result, while car makers have been able to rely on simulation for drag force optimization, they have had to rely heavily on costly and time-consuming wind tunnel testing for wind noise reduction until now.




**Picture 1:** Representation of detailed turbulent flow structures that produce wind noise – iso-surfaces of the Q-criterion (colored by velocity magnitude) on DrivAer generic car introduced in [2]

The main challenge in wind noise simulation for passenger cars and commercial vehicles lies in computing the sound transmission through the vehicle body structure. Whereas tools for simulating the unsteady external airflow have reached a high level of maturity and are able to reliably predict external turbulent pressure fluctuations that serve as the source of wind noise, previous methods for computing sound transmission have proven unreliable. Popular methods that have attempted to calculate sound transmission to-date are transfer functions and Statistical Energy Analysis (SEA). The major drawback of these techniques is that they employ assumptions, empirical correlations and model constants that rely heavily on specific test data. As a result their applicability is quite narrow. They can make reasonable predictions only when used in cases closely similar to the case where the test data was measured. For instance, if empirical correlations in these methods are formulated using wind tunnel test data for one vehicle program, then their accuracy is likely to be unreliable for another vehicle program, or even for major design changes within the same vehicle program. Typically, some amount of testing is essential to give confidence in the model parameters and predictions of SEA methods [3]. Particularly, SEA methods requires testing for confirming acoustic-acoustic and structural-acoustic transfer functions, which can vary significantly with design changes in body shape and design.

Since the predictive range of these methods is narrow and centered around test measurements, car makers have to incur the time and expense of performing extensive testing during wind noise related vehicle development.




**Picture 2:** Deterministic Aero-Vibro Acoustics (Dava) – implementation of Dava simulation in three steps

## New Deterministic Method

In contrast to SEA, a deterministic method is based on first-principles and does not require empirical correlations such as transfer functions. A classic example of a deterministic method is Computational Fluid Dynamics (CFD) used for simulating air flow around the vehicle. The method is based on rigorous solution of fundamental physical equations and the only required inputs are simple case specific parameters such as vehicle speed, ambient temperature, and material properties of air.

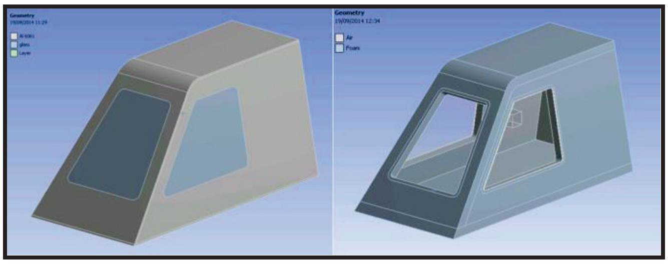
Such a deterministic method has now been developed by ANSYS for predicting automotive wind noise. It solves fundamental physical equations of fluid dynamics, structural mechanics and acoustics, to compute all aspects of wind noise in unison: generation, transmission, propagation. It is referred to as Deterministic Aero-Vibro Acoustics (Dava), where “Aero” represents aerodynamics of the external air flow which generates sound, “Vibro” stands for vibrations of the vehicle body structure which transmit outside sound to the interior of the vehicle, and “Acoustics” represents acoustic wave propagation inside the vehicle cabin that takes sound from the vehicle body to the driver’s ears.

A Dava simulation is implemented in three steps as visualized in picture 2. First a transient CFD simulation of the external airflow is conducted with scale-resolved turbulence models such as Large Eddy Simulation (LES). Time-varying pressure which acts as the source of sound is recorded at every grid point on major sound transmitting surfaces such as the side window and windshield. The pressure signals at each grid point are transformed with Fast Fourier Transformation (FFT) and applied as excitations to a structural model of the vehicle body in a structural solver. A harmonic analysis of the vehicle body structure is conducted with Finite Element Analysis (FEA) in the structural solver to compute sound transmission through the body structure. Vibration velocities at all grid points on the inside surface of the vehicle body obtained from the structural acoustic analysis are applied as excitations to a model of the cabin air cavity. A harmonic acoustic analysis of the cabin air is conducted in a FEA solver to compute propagation of sound through the cabin to the driver’s ear. Optionally, the body structural vibration and the cabin acoustic simulations can be conducted simultaneously in the FEA solver with a single combined model of the body and cabin air. This approach is referred to as strong vibro-acoustic coupling, in contrast to the weak vibro-acoustic coupling described earlier.

The key requirements for Dava are (a) comprehensive robust physics solvers for each of the three underlying physics and (b) seamless interconnection between the solvers so that the geometry models, boundary conditions and results from one physics solver can be easily and robustly applied to another solver. ANSYS Fluent (CFD solver) is used for the Aero solution and ANSYS Mechanical (FEA solver) is used for the Vibro and Acoustic simulations, see picture 2. These solvers are hosted inside the ANSYS Workbench platform that provides a standard interface for all simulations and seamless interconnections between solvers. The interface between the Aero and the Vibro solutions automatically records pressure in time domain at all grid points of relevant vehicle body surfaces in the CFD solver, transforms them into the frequency domain, interpolates them to the grid point locations of the structural model and applies them to the relevant surfaces of the FEA solver. Likewise the interface between the Vibro and Acoustic solvers seamlessly interpolates and transfers vibration velocity data.

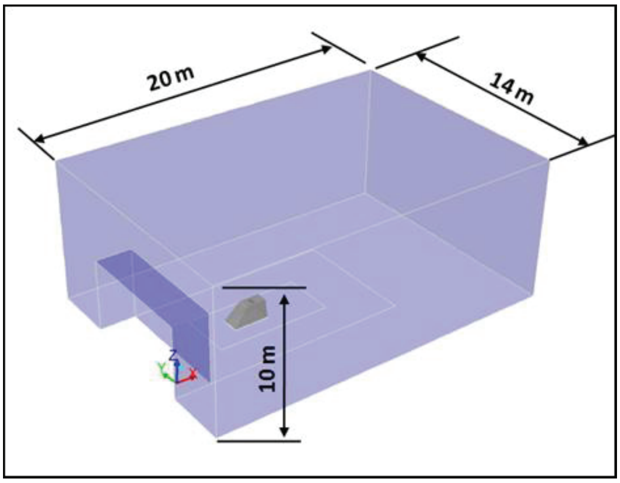
## Validation Example

Hyundai Motors Corporation recently conducted detailed experimental measurements with a simplified model [4] specifically for the purpose of generating an accurate, reproducible data set that could be used for validating generation, transmission and propagation of wind noise, see picture 3.

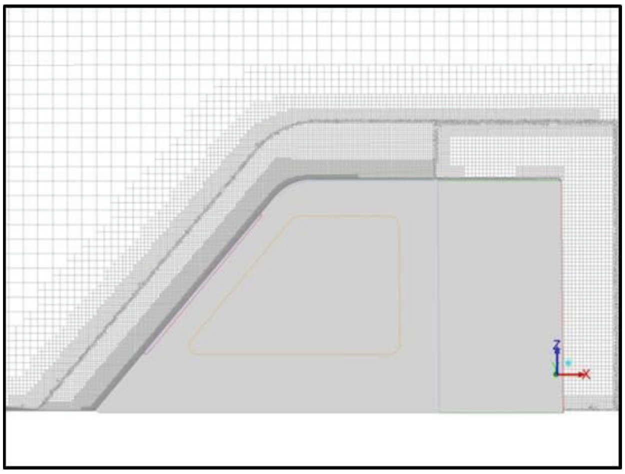


**Picture 3:** Hyundai Simplified Model (HSM): external (left) and internal (right) shape and material

This has been used as one of the validation tests for the Dava method. The simplified model is a trapezoidal vehicle body that generates wind noise generating fluid structures similar to a commercial vehicle shape, including a signify cant front stagnation region, A-pillar vortex, and separation and reattachment regions on the roof. The model has glass on the front and sides that acts as windshield and side windows, as well as an inner hollow space lined by sound absorption materials that acts as the cabin. Measurements are reported [4] from detailed tests including Frequency Response Function (FRF) tests for calculating damping loss factor of each pane, inner cavity reverberation time test, vibration tests. Key material properties such a density, Young's modulus, Poisson's ratio and Biot's parameters are reported for all materials involved. Wind tunnel tests were conducted at 110 km/h and 130 km/h wind speed and 0° and 10° yaws. Time varying static pressure was reported on numerous points on the outer surface of the model as well as on the inner surface in the cabin air cavity. Likewise, sound pressure was reported at a microphone placed in the cabin at a point representing the driver's ear. Picture 4 shows the placement of the vehicle inside the virtual wind tunnel, which exactly represents the real wind tunnel dimensions. A 55 million cell CFD model with first cell height of 0.05 mm was used for the Aero (CFD) portion of the Dava simulation. Picture 5 shows a cut through the hybrid computational mesh.

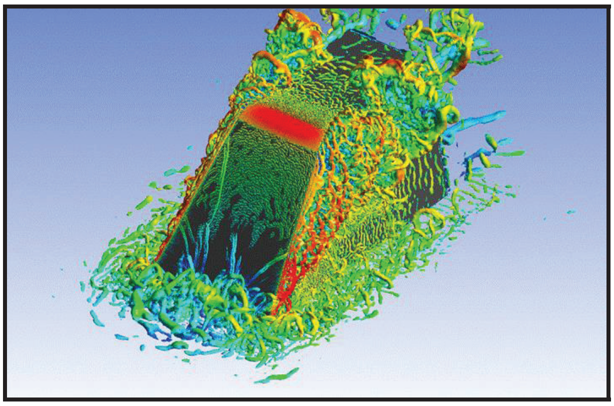



**Picture 4:** Hyundai Simplified Model (HSM): external (left) and internal (right) shape and material



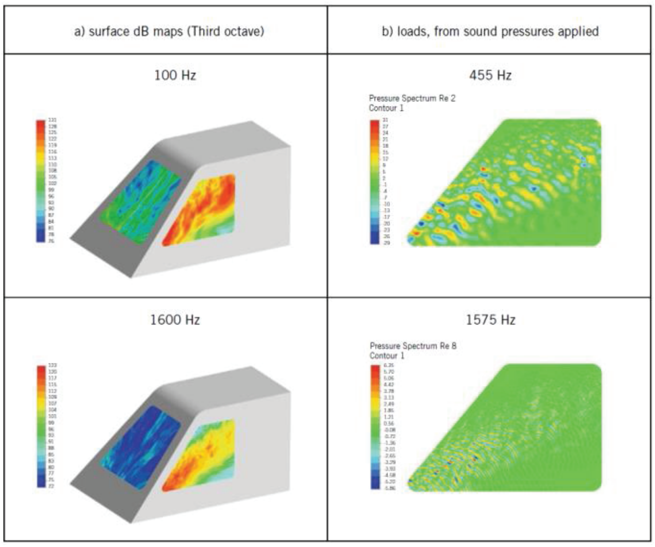
**Picture 5:** Hyundai Simplified Model (HSM): external (left) and internal (right) shape and material

Transient flow simulation was conducted with the Delayed-Detached-Eddy-Simulation (DDES)-SST k-omega model at a 0.2 µs time step with the ANSYS Fluent CFD solver. Unsteady RANS-models often fall short of capturing coherent structures that are responsible for significant tonal and broadband noise. Evidently, LES and RANS/LES-hybrid approaches are better suited for that task [5]. Picture 6 shows the instantaneous turbulent flow-field. Near the wall, turbulence is modelled, away from the wall, it is resolved.



**Picture 6:** Instantaneous flow-field – iso-surfaces of the Q-criterion (colored by velocity magnitude)

Surface dB maps from the CFD simulation, picture 7 (a), show the location of prominent sound sources in two different frequency bands (100 and 1600 Hz). After transforming the time-signals of the pressure into the frequency domain by means of FFT, this complex pressure will be mapped as loads onto the structure-side of the interfaces. The real part represents the resistance and the imaginary part represents the reactance. Picture 7 (b) shows the mapping. Structural harmonic simulations were conducted with the ANSYS Mechanical solver at 240 frequencies from 0 to 2000 Hz. Table 1 and 2 are showing the material properties for the Vibro and Acoustics simulation.




**Picture 7:** Surface dB maps on windshield and side window (a – left side); loads on the side window, transferred from CFD simulation to structural simulation in frequency domain (b – right side)

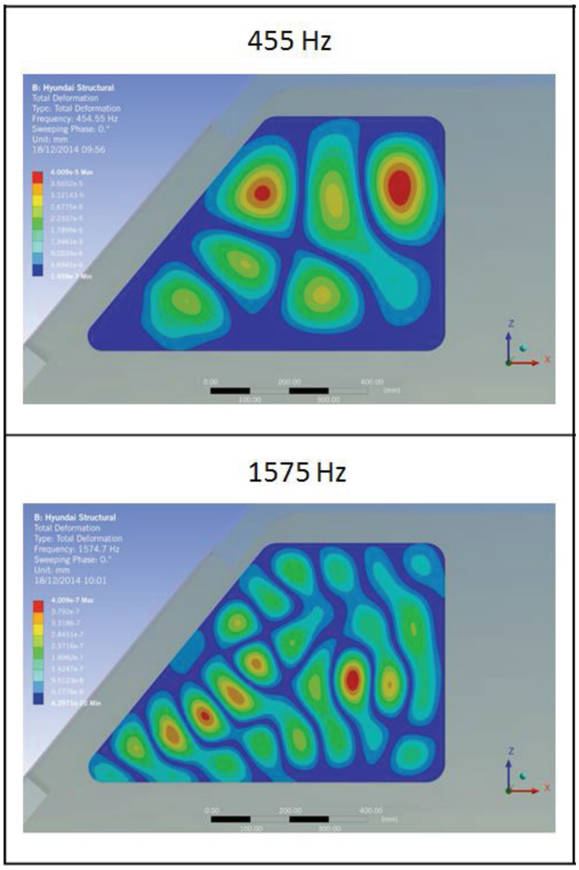
Displacements of the glass inner surfaces, picture 8, computed from these simulations were applied as loads to a model of the cabin air cavity with 1.3 million nodes.

**Table 1:** Properties for Vibro simulation

| Properties | Glass | AL6061 | Heavy Layer |
|---|---|---|---|
| Thickness (mm) | 4 | 12 | 1 |
| Density ($kg/m^3$) | 2500 | 2700 | 2000 |
| Young's Modulus (GPa) | 70 | 69 | 0.04 |
| Poisson's ratio | 0.22 | 0.33 | 0.45 |

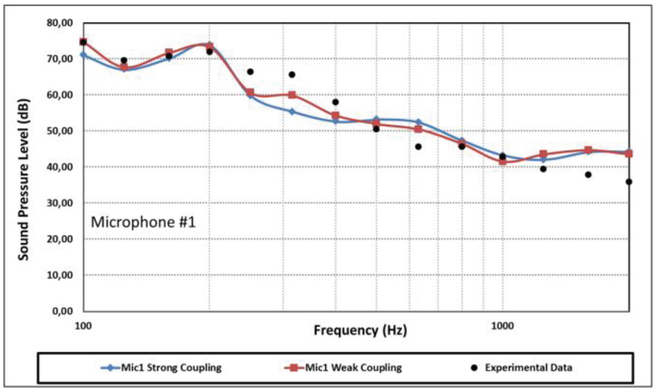
**Table 2:** Properties for Acoustics simulation

| Properties | Air | Foam |
|---|---|---|
| Mass Density ($kg/m^3$) | 1.2 | 1.2 |
| Sound Speed (m/s) | 343 | 343 |
| Fluid Resistivity ($Ns/m^4$) | - | 6.83E+16 |
| Porosity | - | 0.879 |
| Tortuosity | - | 3.31 |
| Viscous Length (m) | - | 9.483e-10 |
| Thermal Length (m) | - | 1.2174e-10 |




**Picture 8:** Displacements of the inner surface of glass for 455 Hz (upper) and 1575 Hz (lower) transferred from body structural harmonic simulation to the cabin air cavity acoustics simulation

A harmonic acoustic analysis of the cabin air, which represents the final acoustics simulation, was conducted with the ANSYS Mechanical solver. This yielded sound pressure levels at the selected microphone locations in the cabin, picture 9. Dava simulation predictions are seen to match closely with experimental results within 5 dB at most points on the spectrum – with a maximum deviation of 10 dB at a few points. The picture shows the results of a strong (blue line) and a weak (red line) coupling.




**Picture 9:** Calculated sound pressure levels at an interior microphone location in the cabin with Dava

## Conclusion

Though wind noise is the top quality concern of automotive customers, it has been challenging to simulate accurately since rigorous wind noise computation methods were not available, recently. For a first-principles computation of wind noise without use of empirical correlations, transfer functions and experimental calibration, three physical problems need to be solved in unison – aerodynamics for sound generation, vibration for sound transmission through the vehicle body, and acoustics for propagation of sound in the vehicle cabin.

A new Deterministic Aero-Vibro-Acoustics (Dava) method has been developed by ANSYS that performs simulations of each of these three aspects with rigorous CFD and FEA methods. This Dava method also overcomes the considerable challenge of connection and data exchange between the various solvers needed for simulating the three different physics – by using the ANSYS Workbench as a platform. The method runs in this single software platform that hosts the CFD and FEA solvers and seamlessly interconnects them for ensuring efficiency and robustness of the solution process. Test cases confirm that this method accurately predicts sound inside the vehicle cabin up to frequencies of 2000 Hz.

## Literature

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