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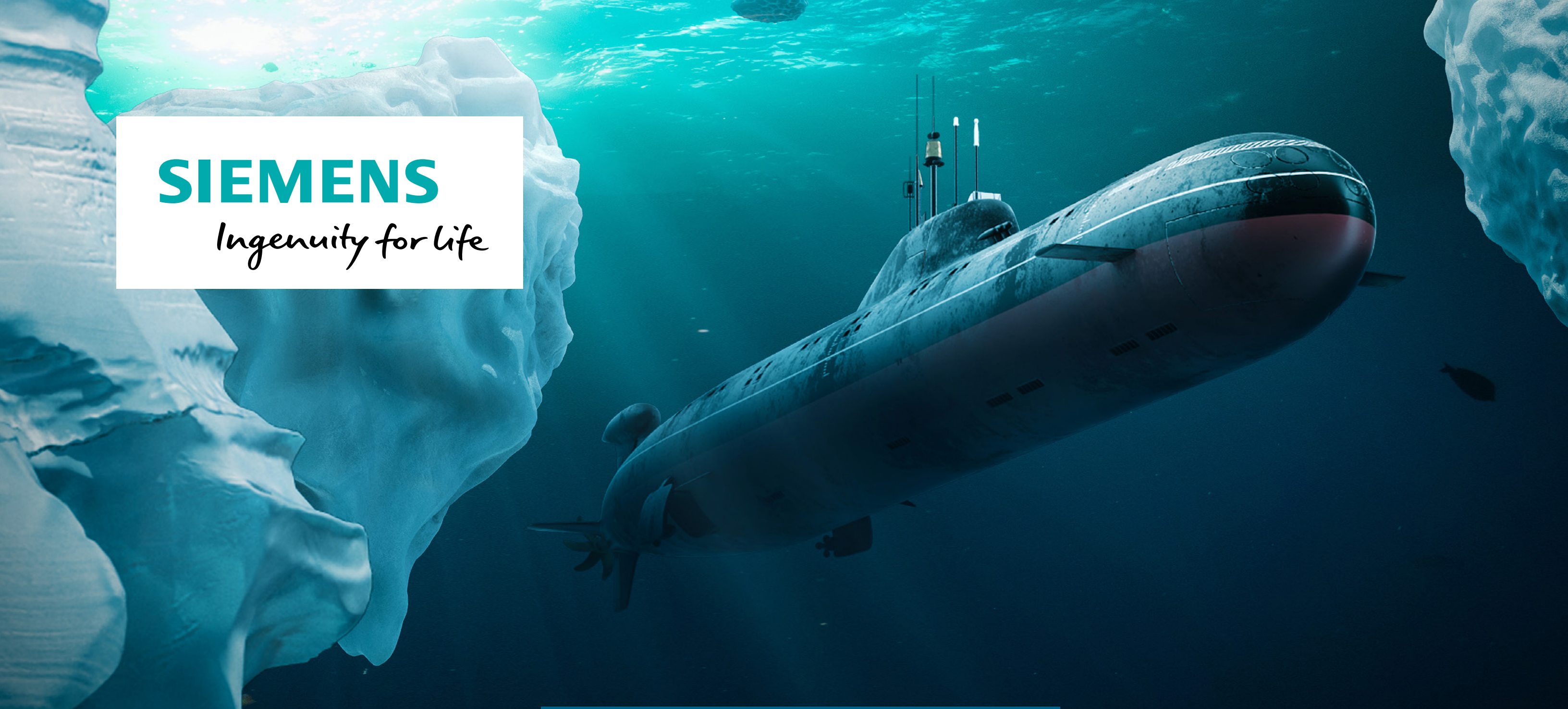


Siemens Digital Industries Software

Broadband vibro-acoustics

Simplifying modeling and speeding up simulations

Executive summary

Simcenter™ 3D software acoustic modules from Siemens Digital Industries Software include two key innovative technologies, finite element method with adaptive order (FEMAO) and automatically matched layer (AML), which simplify modeling while solving wave propagation problems and speeding up vibro-acoustic simulations. With these technologies, an acoustic simulation specialist and a general finite element (FE) analyst can easily simulate broadband vibro-acoustic problems.

Abstract

Using finite element method (FEM) to solve the Helmholtz equation and predict acoustics/vibro-acoustics behavior of products is an established solution. However, there is no way to avoid a tradeoff between meshing effort and computational cost while solving a vibro-acoustic problem over a large frequency range. Two key innovations discussed in this paper, FEMAO and AML, are used to simplify modeling while speeding up vibro-acoustic simulations. The computational efficiency and accuracy are demonstrated using acoustics scattering on a submarine and a pass-by noise application for automotive.

The current state of broadband vibro-acoustics

Although predicting vibro-acoustics behavior of products is quite common (figure 1), solving such acoustic wave propagation problems over a broad operating frequency using classical FEM raises some unique challenges. This is especially true for the degrees-of-freedom (DOF) of the mesh elements, which should be sufficient to accurately capture the wave propagation and limit dispersion error.

A fine mesh that accurately captures the highest frequency can be computationally expensive for lower frequencies. Alternatively, refining meshes for each frequency is an overwhelming task and can hamper simulation viability. For exterior acoustics, an additional challenge is the infinite size of the exterior radiation domain, which is difficult to manage with conventional low-order FEM.

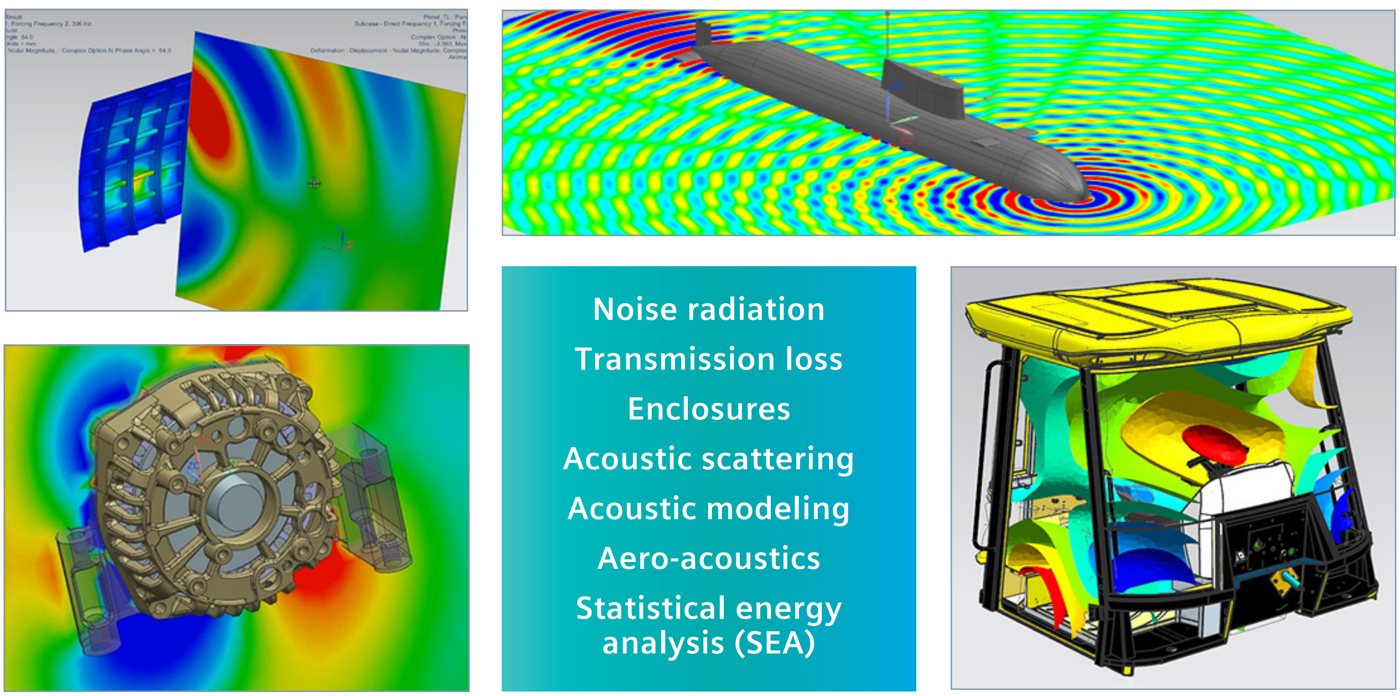


Figure 1. Vibro-acoustic applications.

Breakthrough acoustic modeling techniques

Two key innovative technologies, FEMAO and AML, are included in Simcenter 3D acoustic modules, which help eliminate the complexity associated with solving broadband vibro-acoustic problems.

These innovative solutions are the result of research collaboration between Siemens Digital Industries Software and leading academia and end users, who provide methodology validation in their cases of interest. In particular:

- FEMAO was developed as part of an Engineering and Physical Sciences Research Council (EPSRC) funded engineering doctorate program together with the University of Southampton [1] (see https://epsrc.ukri.org/)
- AML was developed as part of the Flemish Agency for Innovation and Entrepreneurship (VLAIO) [2] funded research and development (R&D) project known as MIDAS together with KU Leuven [2] (see https://www.vlaio.be)

Finite element method with adaptive order

The first key technology is FEMAO in which a high-order FEM method is used in conjunction with an automatic a priori error indicator. With this approach, engineers only need to input a single coarse mesh and the desired accuracy, and the solver automatically selects the order of interpolation in each element at each frequency to obtain a target accuracy while minimizing the cost. An optimal model size is hence obtained for each frequency, allowing the user to perform the broadband vibro-acoustic analysis on the full frequency range with minimal user intervention (figure 2).

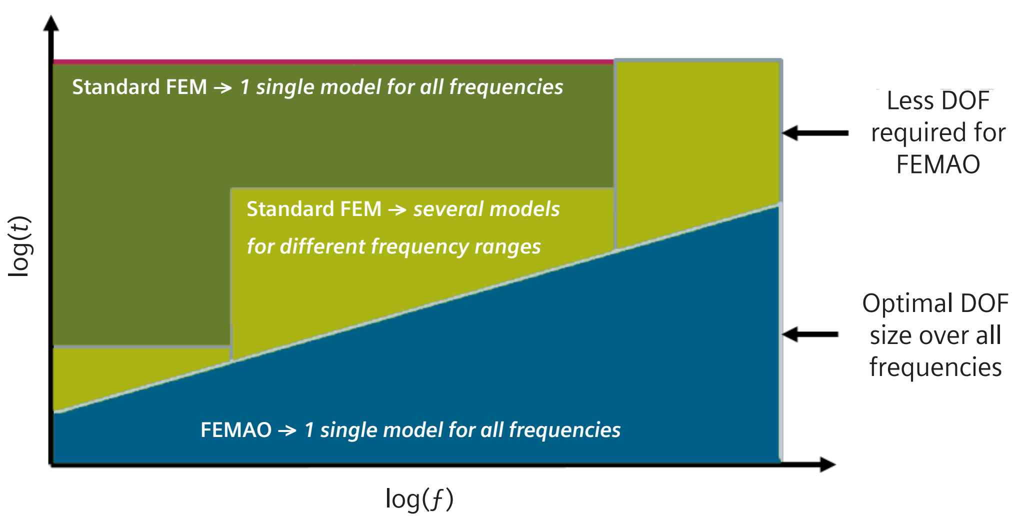
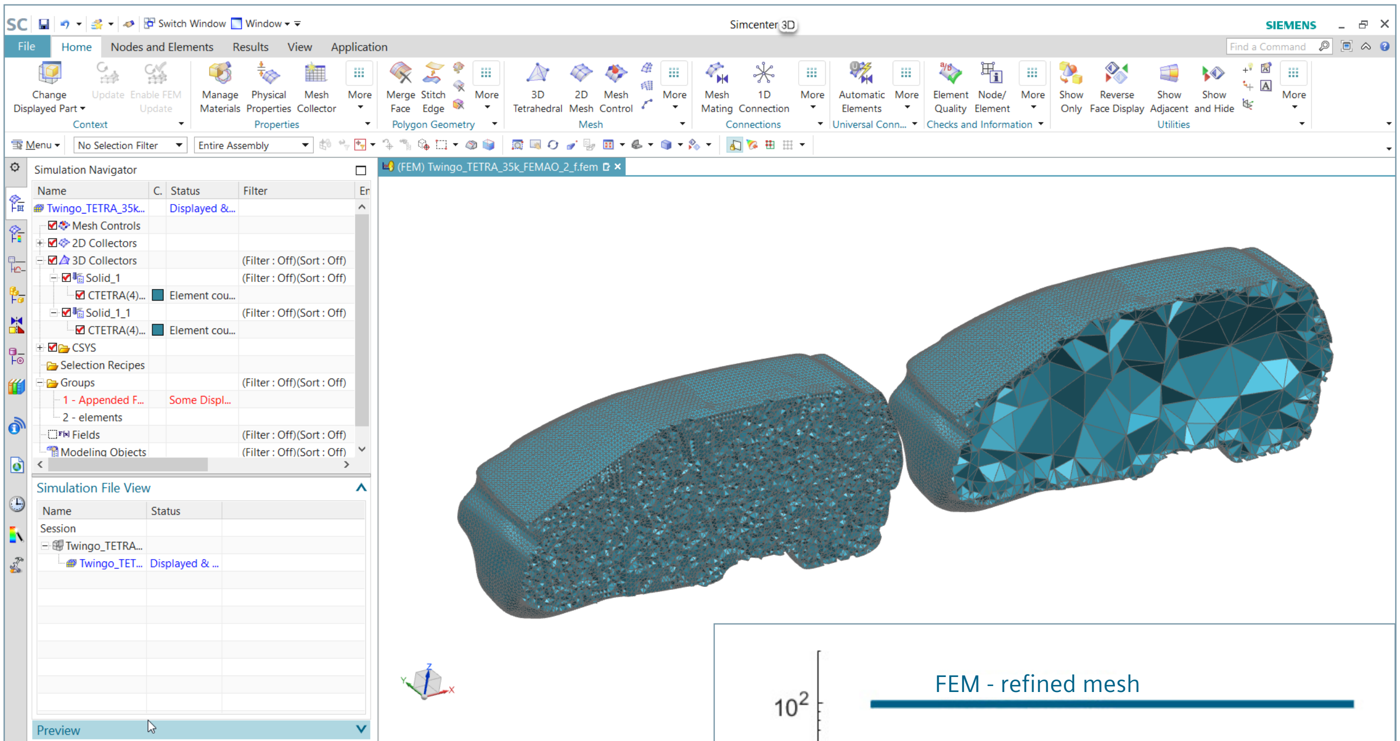


Figure 2: Model DOF comparison of FEMAO and FEM.



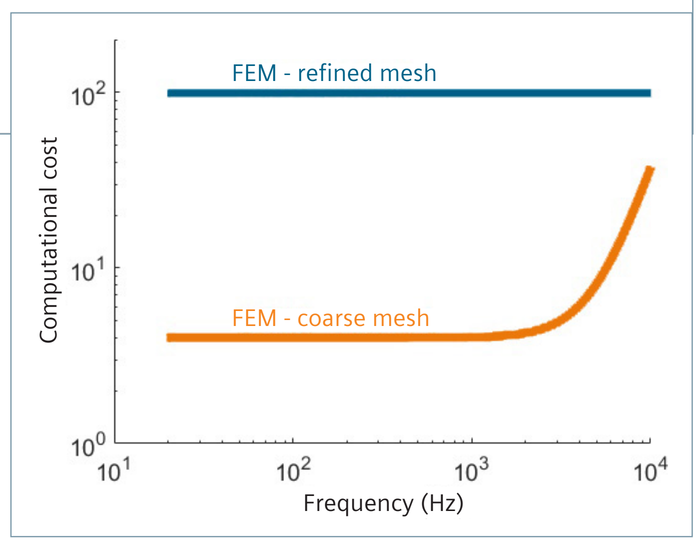


Figure 3: Performance comparison of FEMAO and FEM.

For a representative interior vibro-acoustic case in the automotive industry, figure 3 compares the standard FEM mesh tuned for a certain frequency limit and the FEMAO mesh for the same frequency limit. The frequency versus solution curve shows that:

- FEMAO is much faster at low frequencies (when the coarse mesh in combination with a low order of the shape functions yields an efficient prediction model). This can be seen by comparing the solution time of standard FEM (in blue) and the FEMAO mesh (in orange)
- FEMAO is also more efficient at high frequencies (the solving time for FEMAO in orange still factors lower than standard FEM in blue)

Automatically matched layer

The second key technology is AML, a flexible and efficient wave-absorbing method for free-field exterior acoustic applications. In practice, the solver automatically detects the minimally convex, arbitrarily-shaped surface around the radiating object. An AML property is then applied on this surface. This AML property automatically extrudes a virtual perfectly matched layer (PML) region that surrounds the FEM region where the incoming waves are absorbed. The element order and the number of layers in the PML region are determined automatically by the solver based on the input mesh and the frequency of interest, without further user intervention. As can be seen from the turbocharger example in figure 4, this offers a large mesh size benefit compared to traditional methods (including applying a *ρ-c* boundary condition and using an infinite FEM approach).

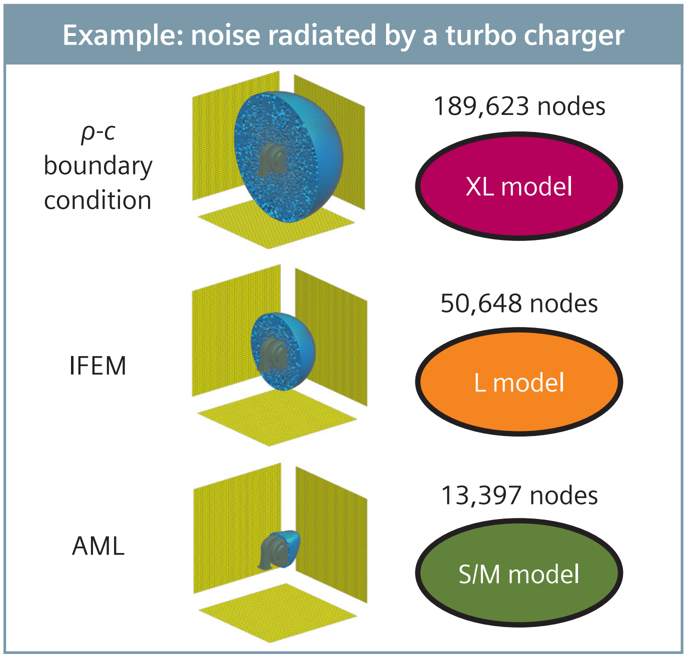


Figure 4: AML enables extremely lean models.

By integrating breakthrough methodologies such as FEMAO and AML into Simcenter 3D acoustic modules, Siemens Digital Industries Software democratizes the usage base of simulation methods, from acoustic engineering experts to the much wider general FE analyst community. Companies can expand vibro-acoustics knowledge across a team of general analysts, who jointly seek to balance vibro-acoustic targets with other multi-attribute performance targets.

Industrial validation

Acoustic scattering of a submarine

The benchmark target strength simulation (BeTSSi) submarine, which has been the object for several studies [1][4], is used as a reference model. The submarine is 62 meters (m) long and its main body has a mainly cylindrical radius of 3.5m. From the geometry, a two-dimensional mesh is generated that discretizes the submarine and follows its exterior boundary. The surrounding FE mesh has been created using Simcenter 3D (figure 5). [3]

Using a mesh size of 250 millimeters (mm), the FEMAO technology can solve for a frequency of 6.5 kilohertz (kHz) with polynomial orders from 6 to 9 depending on the target accuracy. In the paper entitled, "Evaluating Submarine Sonar Stealth Using an Adaptive-Order Finite Element Method," [5] a study was done for this case that compared a standard FEMAO solution (order mean value at 7 to 8) and a coarse FEMAO solution (order mean value at 6 to 7). For exterior acoustic radiation, the AML layer is created automatically by the solver just around the finite element mesh shown in figure 5.

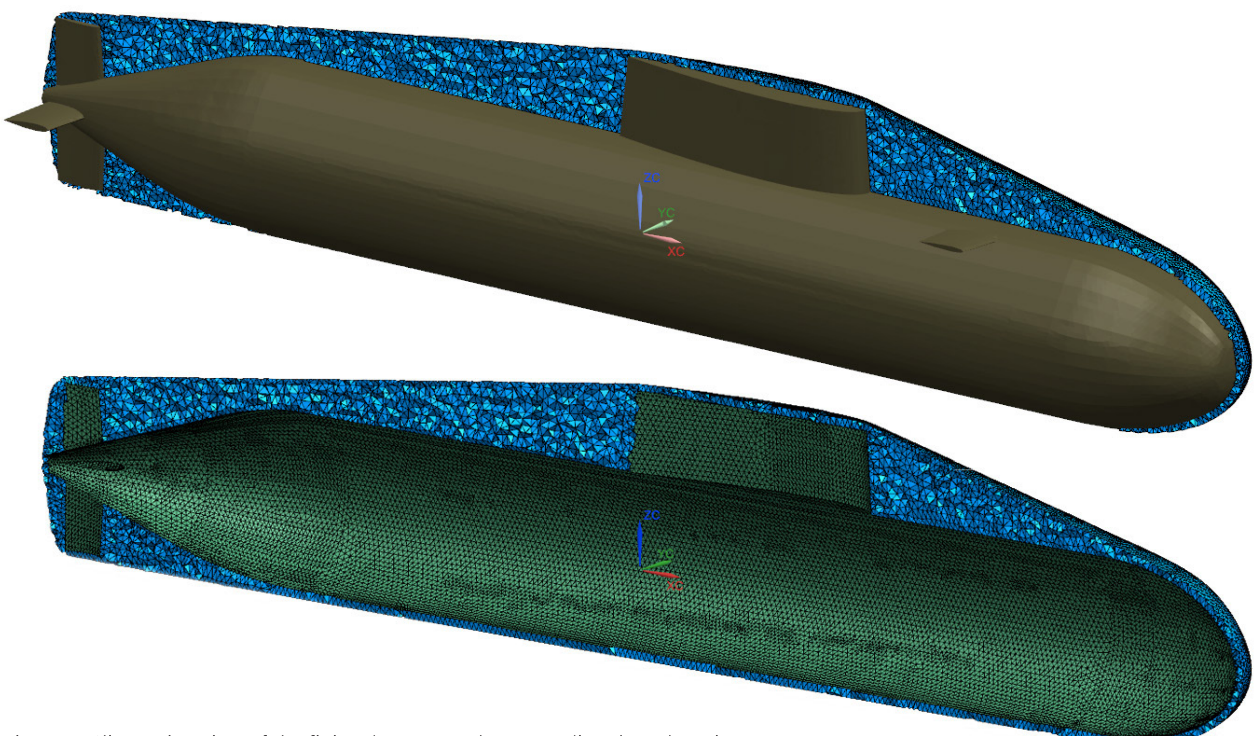


Figure 5: Clip-section view of the finite element mesh surrounding the submarine.

In the acoustic analysis, an incoming acoustic plane wave is scattered on the immersed submarine. This step (shown for an incident plane wave at 0 degrees in figure 6) is repeated for different incident plane wave angles, so the monostatic target echo strength (TES) can be computed. [5] The monostatic TES is a measure of the scattered acoustic pressure field with respect to the incident acoustic pressure field as a function of the angle, providing a single value for the total reflection of the submarine at that angle. The TES curve for the submarine is shown in figure 7, and is calculated with the reference boundary element method (BEM) and standard FEMAO. It can be seen the two solutions match nicely, demonstrating the fully FEM-based acoustic prediction process is possible for such large models. More details on this case are provided. [5]

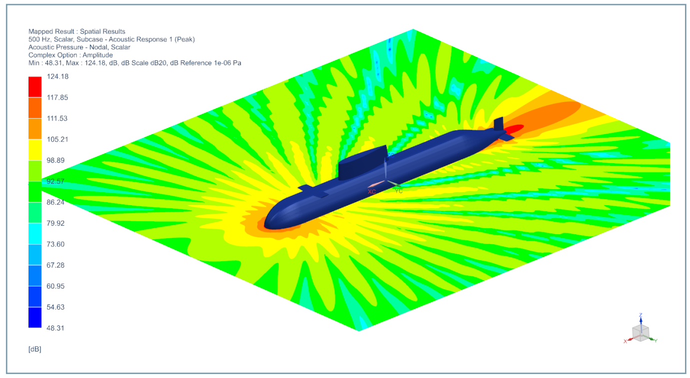


Figure 6: Acoustic scattering by an immersed submarine: an example of a scattered field for an incident plane wave at 0 degrees. [6]

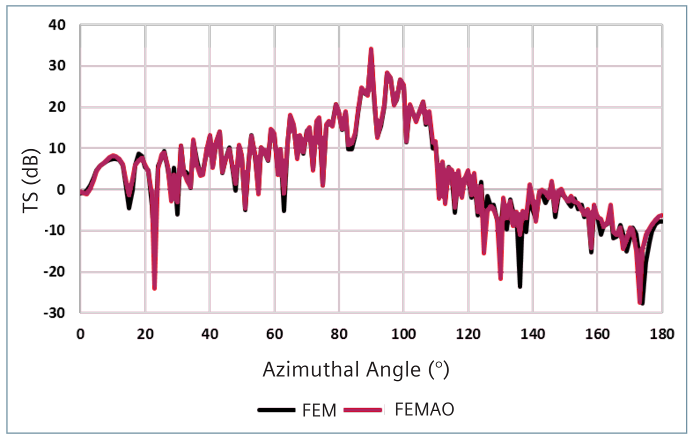


Figure 7: Acoustic radiation by an immersed submarine: The target echo strength gives a measure for the scattered acoustic pressure as a function of the incident plane wave angle.

Automotive pass-by noise simulation

Automotive pass-by noise is subject to a new regulation: Economic Commission for Europe (ECE) R51.03 [6], which will impact the vehicle development process [7], particularly in the homologation phase. ECE-R51.03 is based on a revision of the International Organization for Standardization (ISO) 362 standard [6] and requires more tests in different conditions. To avoid costly and time-consuming design iterations, enhanced engineering techniques are used to quantify and rank the contributions of separate subsystems to the overall pass-by noise level, such as intake, powertrain, exhaust, tailpipe and tires. These techniques are not only efficient troubleshooting tools for reducing noise, they are also increasingly employed for precise target setting early in the design process. A general presentation of the pass-by noise regulation for vehicle homologation, along with an overview of engineering techniques for source contribution analysis in the pass-by noise context. [7] The enhanced focus on pass-by noise can partially be addressed by calculating the transfer paths from the installed engine in a virtual environment (figure 8).

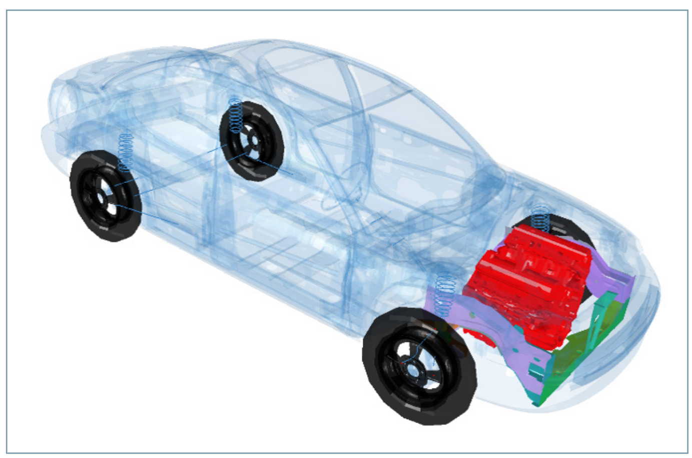


Figure 8: Pass-by noise analysis case: engine as installed airborne noise source.

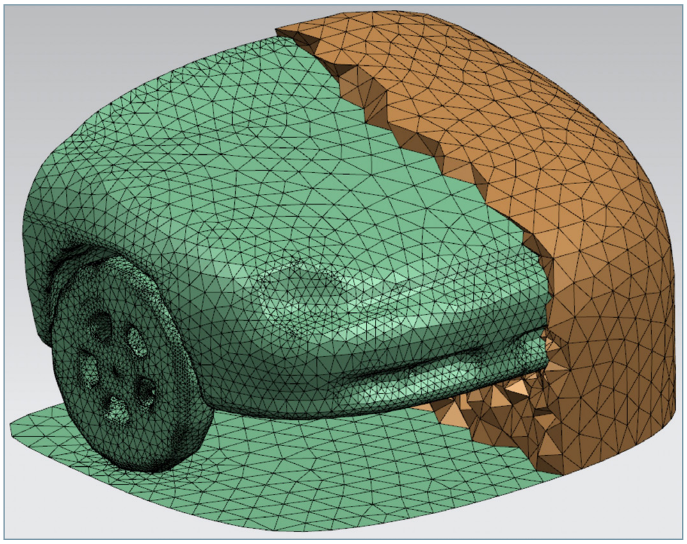


Figure 9: Pass-by noise analysis case: the front of the car is modeled with FEMAO technology.

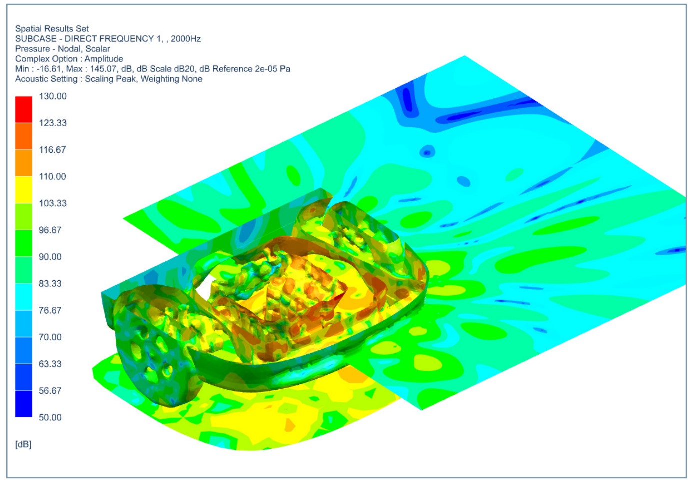


Figure 10: Pressure field (decibels) for one of the acoustic monopole sources placed in the engine bay. This resulting pressure field can be interpreted as the virtual transfer path calculated from that acoustic monopole source location.

A FEMAO-based approach to exterior acoustics [3] is used around a half-car model (figure 9), with AML technology applied directly by the solver just around the FEMAO mesh to accurately predict the acoustic radiation of the engine as installed in the vehicle.

In the framework of the pass-by noise analysis, microphones are placed a specific distance from (and parallel to) the car. In the current example, the microphones are placed at 7.5m.

For the virtual pass-by noise analysis, the engine is considered as an installed airborne noise source within the structural car model, as shown in figures 8 and 9. An example of the acoustic pressure field for one of the acoustic monopole sources (for instance, an example of a virtual transfer function) is shown in figure 10. An example of the acoustic pressure response at one of the pass-by noise evaluation points is shown in figure 11. The sound pressure level (SPL) is computed with a direct frequency response using FEM AML in one case and FEMAO AML in the other case. Both solution cases provide equivalent results, with some differences at higher frequencies in which the FEMAO AML is expected to be more accurate since it relies on the high-order shape functions. In terms of computational time, the benefit of FEMAO AML over FEM AML is clearly demonstrated.

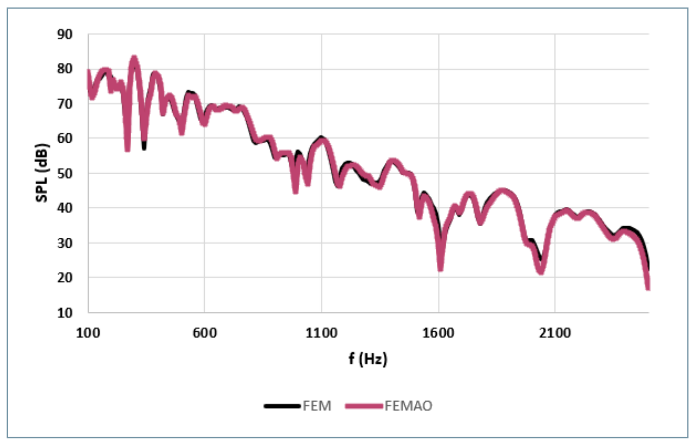


Figure 11: Pressure response (decibels) at a pass-by noise evaluation location for a unit acoustic monopole source example. The FEMAO AML results are achieved about 4.5 times faster than the FEM AML – a great advantage.

System specification for pass-by noise simulation.

Windows 7 Desktop
28GB RAM
10 cores, 20 threads
2.5 GHz
No SSD

	SOL108	
One node smp=8	**FEM AML**	**FEMAO AML**
Frequencies	100-2500 Hz	100-2500 Hz
Time forced response	97 minutes	22 minutes

Conclusion

The simulation of vibro-acoustic problems based on classical FEM creates several issues. For an error-free and efficient computation, the mesh needs to be refined according to the frequency of the problem being solved. However, it is rarely performed as this proves demanding for engineers. Using a single fine mesh resolved for the highest frequency of interest to cover a broad frequency range, vibro-acoustic simulation increases the computational cost, especially while solving lower frequencies. Secondly, these practical considerations are subject to the more fundamental limitation of the conventional finite element methods at higher frequencies. For exterior acoustics, an additional challenge is the infinite size of the exterior radiation domain, which is difficult to manage with conventional low-order FEM.

Two key innovative technologies available in Simcenter 3D acoustics, FEMAO and AML, are included to help you master the mesh complexity for your vibro-acoustic applications. By combining FEMAO and AML, the key mesh-based disadvantages of standard FEM are eliminated so the broadband frequency range for interior and exterior acoustics can be predicted based on FEM.

Acknowledgements

FEMAO and AML were integrated into Simcenter 3D as part of the VLAIO project entitled, “Holistic Environment for Advanced Vibro-Acoustic Engineering for Non-Specialists” (HEAVENS), a collaboration between Siemens Digital Industries Software and MAYA, with the support of EUREKA. EUREKA is an intergovernmental network launched in 1985 to support market-oriented R&D and innovation projects by industry, research centers and universities across all technological sectors and MAYA is a Canadian partner. One of the key objectives of HEAVENS was to democratize the acoustics simulation methodologies in the product lifecycle management (PLM) process. We gratefully acknowledge VLAIO and EUREKA for their support of HEAVENS.

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