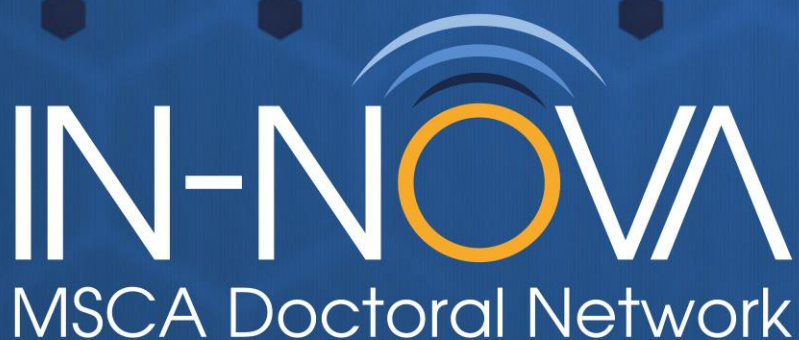




Active reduction of noise transmitted into and from enclosures through encapsulated structures.

Marie Skłodowska-Curie Actions

project no. 101073037

Review on Cabin Noise Simulation Framework
WP2 – Noise reduction in vehicle and aircraft cabins (out-in problem).

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Introduction

Acoustic performance is nowadays a primary concern for the industry since customer requirements are increasing and a good performance can easily differentiate a product. Noise, Vibration, and Harshness (NVH) engineers need to use the correct methods to optimize conflicting design criteria such as (i) emitted noise (interior and exterior) and vibration levels, (ii) safety, (iii) cost, (iv) efficiency, and (v) ecological impact.

Numerical simulations have been used for decades to solve various engineering problems. It is the standard in the industry to support the designing of complex components and systems. It is used to optimize products, troubleshooting existing issues and providing deeper understanding on physics to enable engineers to take appropriate decisions.

This review aims at describing the different acoustic and vibroacoustic simulation frameworks that are commonly employed for interior noise prediction, especially inside vehicle and aircraft cabins.

The review starts by introducing the basic concept of the established acoustic and vibroacoustic simulation methods: (i) Finite Element Method (FEM), (ii) Boundary Element Method (BEM) and (iii) Statistical Energy Analysis (SEA). While widely used in the industry and literature, those methods have also been improved to reduce computational time and memory allocation as described in Section 2. Another important aspect of interest to the NVH design engineers is to understand the contribution of each excitation source, each path from source to the receiver, and each radiation component. Section 3 provides with an overview of such contribution and path analysis methods. Then, Section 4 deals with the application of the described methods to the specific cabin noise prediction in automotive and aerospace industries, highlighting the excitation sources and common post-processing analyses. Finally, the review concludes by exposing the remaining challenges of such techniques and the subsequent research contributions planned within IN-NOVA project.

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1. Numerical methods for vibroacoustic simulation

In this section the most established methods for vibroacoustic simulation are presented. A detailed description of methods and frequency of application can be found in [1].

1.1. Finite Element Method

Finite Element Method (FEM) is a well-known and widely used numerical method to predict physical responses. Different physics can be calculated via FEM. It is a deterministic approach based on the discretization of a geometry in a discrete number of smaller elements that are mathematically represented by simple functions (shape functions). For example, in mechanical analysis (including vibration) linear or quadratic functions are typically used. The results are calculated on the nodes of the system and depending on the analysis, more than one field variable / Degree of Freedom (DOF) is calculated in each node. A set of algebraic equations is built after the discretization step. The resulting matrices are solved using dedicated numerical solvers.

The application of FEM to acoustics dates to 1965 [2]. The basic differential equation to be solved is the second order Helmholtz equation (frequency domain) and the pressure is calculated at each node. To solve vibro-acoustic coupled problems it is necessary to simultaneously solve for the fluid pressure and the structural deformation. This means that an acoustic FE and a structural FE model need to be developed and coupled through the matrixial formulation. Consequently, the discretization of both domains and their coupling may significantly increase the memory allocation and solving time. It is also relevant to mention that, since domain discretization is needed, the FEM is suitable for interior noise calculations but not directly applicable to external noise simulation.

A typical element size for acoustic is 6 to 10 elements per wavelength. That means that the model size (number of DOF to be computed) increases drastically with the frequency of analysis. Due to computational efforts, the FEM is practically restricted to low-frequency applications since a more refined model is needed to capture high frequencies accurately.

It is important to mention that the definition of low and high frequency is problem-dependent since it is related to the size of the domain under study and the wavelengths of the dynamic response. Given the fact that the wavelength decreases with increasing frequency, it means that at low frequencies, the order of magnitude between the system size and the model size are similar, given a response with well-separated modes. At high frequencies the wavelength is much smaller than the domain and the modal density increases, i.e. the response becomes more sensitive to small variations [1]. More details on frequency range are given in the application sections.

1.2. Boundary Element Method

The Boundary Element Method (BEM) is a numerical approach to solve partial differential equations by focusing on the boundaries of the domain rather than on the entire volume. Since it only requires a mesh of the boundary, a smaller number of elements w.r.t. the finite element method is needed for the

same level of accuracy and element size [3]. This characteristic makes it particularly suitable for problems with complex geometries, such as car cabins, where traditional finite element methods may require a significant computational effort. To be specific, this method is computationally more efficient than FEM for problems where there is a small surface/volume ratio [4].

The fundamental idea behind the BEM is to convert a volume integral equation into a surface or boundary integral equation. This is done by using Green's identities and approximating the domain integral with a sum of integrals over the boundary elements. There are both direct and indirect formulations for the BEM. Unlike the indirect version, physical acoustic variables (e.g. pressure and fluid normal velocity) are used in the direct formulation of BEM (DBEM), restricting its application to only one side of the surface (interior or exterior). However, the Indirect BEM (IBEM) not only can consider both sides but also doesn't require the surface to be closed [5].

The solution by BEM can reach a high accuracy since it solves the singular integral equation and gets the primary unknown variables on each node without any assumption [6]. Nonbounded external domains can also be studied using BEM. This is because unlike FEM, the Sommerfeld condition accounting for radiation in an infinite medium is automatically satisfied. Sound radiation simulation of engine, exhaust shell, etc. are some main applications for BEM in vehicle noise and vibration modelling. Also, the presence of acoustic treatments can be modeled only using their surface impedances through this method [5]. However, there are also several drawbacks to using BEM. The coefficient matrix created with this method is fully populated and non-symmetric which can make it slower than FEM [7]. Also, these matrices are frequency dependent and do not show positive definiteness [8]. On the other hand, since the method only becomes potentially useful when implemented in software, the computation practicalities such as memory requirements, efficiency, and reliability issues for exterior problems, are of importance [3]. In case of exterior acoustic problems, the conventional BEM fails to provide unique solutions at irregular eigenfrequencies [6].

Several methods have been proposed to improve the computational efficiency of BEM. As an example, the Fast Multipole Method (FMM) divides the geometry into a tree-structure and uses a spherical wave expansion to accelerate both the assembly and solution of BEM [8]. As a method that uses an iterative solver, a preconditioner would be needed to improve its convergence speed for acoustic problems with large wavenumber and complex geometry [9]. An alternative technique for quickly solving the BEM system of equations uses hierarchical matrices. Known as "fast direct BEM", this method recursively obtains the solution of the BEM system based on low-rank approximations, decompositions and by implementing fast inverse algorithms on submatrices [9].

1.3. Statistical Energy Analysis

Statistical Energy Analysis (SEA) is a methodology for simulating vibro-acoustic complex systems in mid and high-frequency ranges from a statistical point of view. The vibro-acoustic systems are sub-structured in different subsystems that exchange energy flows [10]. The geometrical complexities of the system are neglected, and the subdivision of the domain is performed such that the components are defined by simple geometries and junctions [11]. The simplicity of this method resides in representing the coupled system by means of a set of linear equations that describe the energy flows (input, storage,

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transmission, and dissipation) within each subcomponent. While energy denotes the primary variable of interest, other dynamic variables such as displacement, pressure, etc., are found from the energy of vibration [12]. Large vibro-acoustic systems cannot be efficiently simulated in high-frequency range by traditional FEM or BEM methods, since the required number of elements can be extremely high. Figure 1 [13] shows the frequency bands at which the deterministic and statistical methods are valid, for the case of an aircraft cabin.

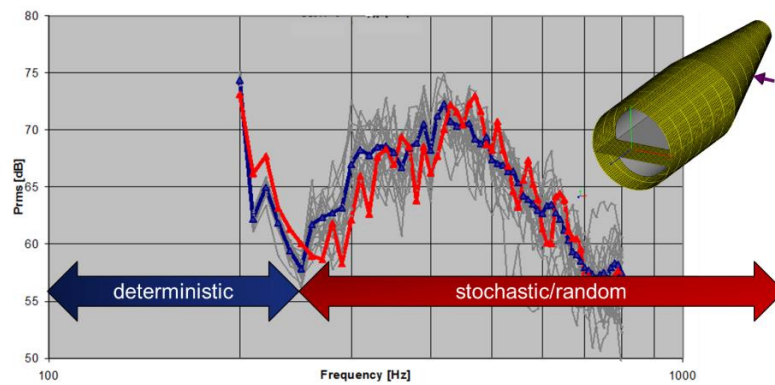


Figure 1. Validity of stochastic methods such as SEA in large vibro-acoustic systems [13]

2. Numerical techniques for efficient simulation

In this section several basic and advanced techniques are described, specifically in the objective to reduce memory allocation during simulation and to reduce computational time.

2.1. Modal Superposition Method

In the field of linear dynamics and FE modelling, Modal Superposition is an efficient method to replace the initial dynamic system of Equation (1) by a reduced size system.

$$M\ddot{u}(t) + D\dot{u}(t) + Ku(t) = f(t), \quad (1)$$

This reduced system is obtained by solving a generalized eigenvalue problem in frequency domain, for which each eigenvalue-eigenvector pair corresponds to a natural frequency and a mode shape of the system. The modal basis composed by all the natural frequencies and mode shapes of the finite element system, is truncated so that only the first eigenfrequencies and modal vectors contribute to the dynamic behavior. The dynamic system is projected into the truncated modal basis, conforming a reduced system of equations with less sparse coefficient matrices, as presented in Equation (2):

$$\ddot{u}(t) + D_m\dot{u}(t) + \Omega^2u(t) = f_m(t), \quad (2)$$

This method is extensively used for analyzing structural, acoustic, and vibro-acoustic systems, and it is effective for simulating low-frequency linear dynamic problems [14].

Since modal reduction is based on solving the eigenvalue problem, thus assuming that there is no excitation, the accuracy of the reduced order model can be improved by constructing a reduced order model that uses the expected input/output locations. One effective way to improve the accuracy is by using Krylov subspace reduction, as is shown by [52-53]. This method creates a Padé approximation of the transfer function between the given inputs and outputs through implicit moment matching.

2.2. Acoustic Transfer Vectors (ATV) and Vibro-Acoustic Transfer Vectors (VATV)

Acoustic Transfer Vectors (ATV) are used to speed up a simulation where you have several load cases and the component radiating the noise and the acoustic domain are not changing. A typical example is a ramp-up of an engine, where different speeds (RPMs) can be solved efficiently. The basic idea is to create an input-output relation using transfer functions between each of your input nodes to the output nodes. For ATVS it means a relation between the structural vibrating surface to a specific acoustic point field (pressure response). You can also use a modal coordinate to represent this relation, this approach is known as Modal Acoustic Transfer Vectors (MATV) [15].

The VATV can be applied in the context of a two-way (strong) coupling. The transfer function is defined between the normal force on a structural node and the acoustic pressure response [16]. The transfer vectors can be created from FEM, BEM, or Ray Acoustics. For radiation purpose the BEM approach is typically used. The computation efficiency comes from the fact that once you simulated the transfer functions you can freely change the excitation load (on the same nodes) to get the acoustic response (in the same response position) with small computational effort.

2.3. Adaptive Order methods for acoustics and vibro-acoustics – FEMAO and BEMAO

The standard approach for FEM and BEM is to use simple low order shape functions inside an element to approximate the solution. A relatively small element size is needed to achieve accuracy with the standard approach. As an alternative formulation, the adaptive order method described in [17] is an efficient technique to reduce computational time and possibly extend frequency range while keeping accuracy. The Finite Element Method Adaptive Order (FEMAO) and Boundary Element Method Adaptive Order (BEMAO) are based on a higher-order hierarchical polynomial shape function of an element. An efficient implementation of those functions is described in [17] where the order is adapted based on two features: the frequency of computation step, and the element size. The paper describes a car cavity test case to emphasize the benefit of the method. In Figure 2, a mesh of more than 1.1 million nodes (FEM) is compared to a mesh of 54k nodes (FEMAO III). The computation time is shown in Figure 3. In low frequencies, the combination of a coarse mesh and low order element implies a very fast solution. For higher frequencies, the FEMAO solution is still more efficient than traditional FEM solver.

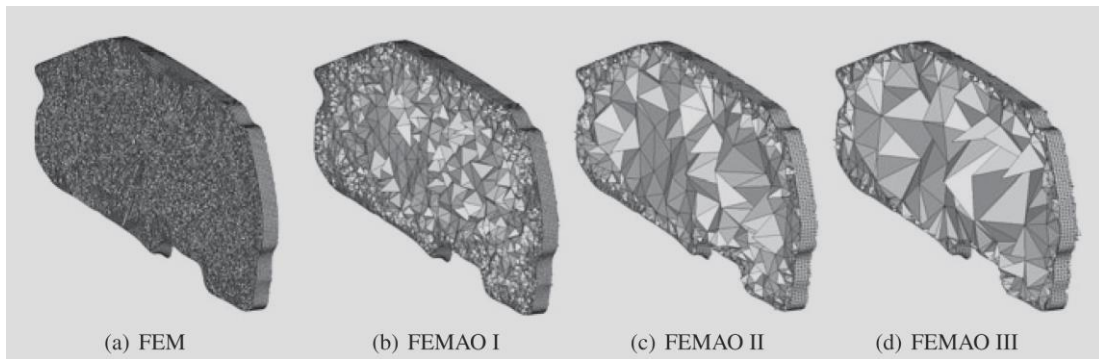


Figure 2. Cross section of the four meshes used for the car cavity test case [17]

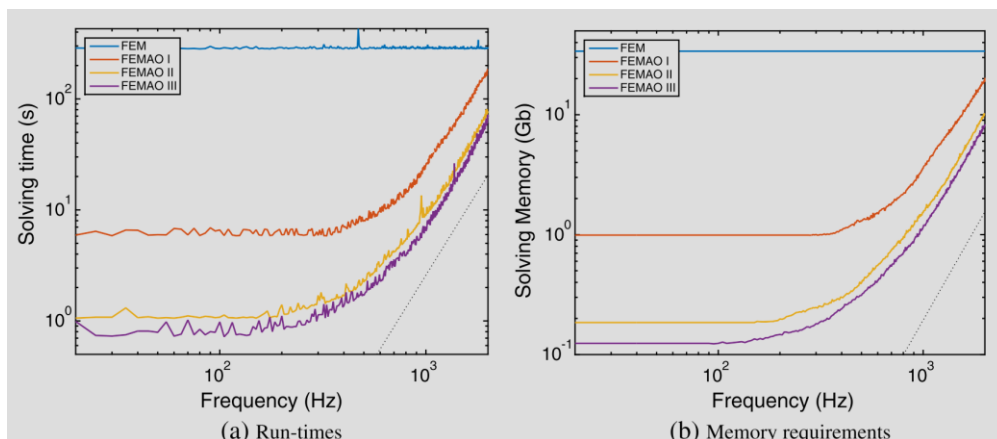


Figure 3. Computational cost of the numerical models as a function of frequency [17]

2.4. Dynamic Substructuring, Component Mode Synthesis

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In the context of FEMs, Dynamic Substructuring (DS) and Component Mode Synthesis (CMS) techniques offer efficient ways to accelerate and enable the analysis of complex models by dividing structural and acoustic domains in subcomponents [18].

The DS technique involves partitioning a complex system into smaller, manageable components. These components are then assembled to analyze the overall system dynamics. The coupling between subdomains must always satisfy two conditions: compatibility and equilibrium. The compatibility of displacements at the interfaces of the neighboring subdomains ensures the continuity condition, while the force equilibrium between components guarantees the action-reaction law [19].

$$\begin{cases} M\ddot{u}(t) + D\dot{u}(t) + Ku(t) = f(t) \\ Bu = 0 \\ L^T g = 0 \end{cases}, \quad (3)$$

Equation (3) summarizes the governing equations of DS. The compatibility condition at the interface is assessed by means of the constraint matrix (B), while the equilibrium condition is stated by means of the localization matrix (L).

On the other hand, CMS involves representing the dynamic behavior of each structural or acoustic component using its natural frequencies and modal shapes [20]. These reduced subdomains are then combined to efficiently analyze the overall system's dynamics. Since the coupling is performed in terms of truncated modal basis of each component, the method is only approximate and can lead to errors associated to high order modes.

3. Contribution Analysis and Transfer Path Analysis

Engineers use simulation to optimize products and one important understanding for NVH improvement is to determine the main sources and paths that contribute to the generated noise. Some techniques to quantify each contribution are explained in this section.

3.1. Transfer Path Analysis

In general, there are two main transfer paths from an exciting source to the receiver object [21]. For instance in the case of a car, the structure-borne transfer path relates to the vibrations transmitted to the vehicle body through the motor mounts and other connections, while the airborne transfer path is characterized by the airborne noise transmission from the motor compartment into the driver cabin. In case of the low and medium frequency range, structure-borne noise accounts for the most important contribution [7]. Time-domain transfer path techniques such as Vehicle Interior Noise Simulation (VINS) are recommended for further analysis when the frequencies and orders of the different excitation sources are known [22]. The Simcenter Testlab software also provides a similar functionality that allows comparing different transfer path contributions by listening to them instead of resorting to 2D graphs (for example, amplitude vs rpm). This method separates airborne noise contributions from those of structure-borne nature, making it possible to determine dominant transfer paths. An example of using TPA to detect the main vibration paths and frequencies associated with the interior noise caused by the electric power steering system of an electric vehicle through measurements of A-weighted SPL can be found in [23]. An in-situ Blocked Force Transfer Path Analysis (BF-TPA) requiring the measurement of vibration at the source and at many mount joints on the transfer path is employed in this paper.

The TPA steps to detect sources of structure-borne noise can be followed as [24]; 1) quantify the operational loads through a direct measurement, the dynamic stiffness method, or matrices inversion-based identification, 2) relate these loads via the transfer path to a target response, e.g. the acoustic pressure. A new operational test is needed for every change in design to predict the effects of subsystem modification using classical TPA. As indicated in Figure 4 [25], the reason is that the interface forces obtained from a classical TPA are not a characteristic of the source alone but of the assembled dynamics [25]. As mentioned in the next section, component-based TPA is an alternative approach to remove this restriction.

As shown in [26], the Panel Noise Contribution Analysis (PNCA) can be implemented for noise quantification and ranking within an electric vehicle's car cabin through multiple sound pressure and particle velocity measurements. In this case, the measurements were made on both the static condition and at constant driving speed on a highway. A high-frequency whistling (whining) noise of 970 Hz was detected and was proved to be mainly perceived from the A-pillars (Figure 5 [26]). Another example of experimentally employing Transfer Path Analysis (TPA) is mentioned in a more recent work on a pure electric vehicle (PEV) [27]. Here, a virtual interior sound quality synthesis method using TPA and Transfer Path Synthesis (TPS) is proposed for identifying the noise transfer paths and noise sources of PEVs. As part of TPA, Transfer Path Synthesis (TPS) involves the synthesis of the total noise and/or sub-system noise contributions. Not only it can reproduce the analyzed situation but also can alter the entire system and exchange its components [28]. Instead of sound pressure levels, the work recommends using

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psychoacoustic parameters of sound quality as the evaluation index of the interior noise synthesized by TPS.

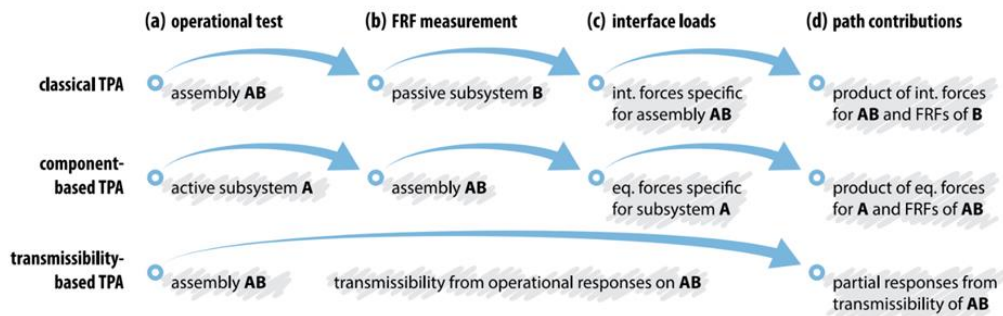


Figure 4. The stepwise workflow for different TPA categories [25]

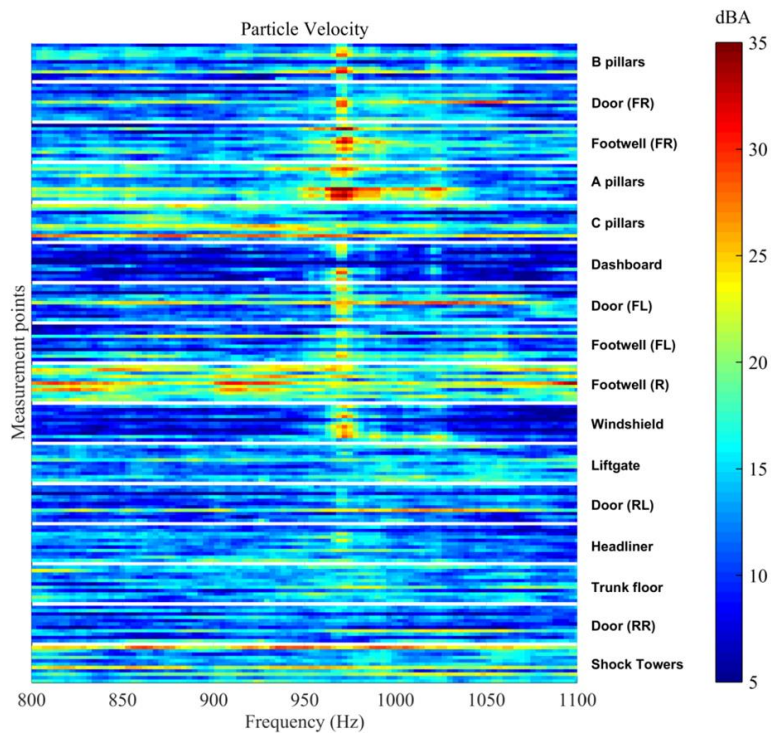


Figure 5. The particle velocity spectra of different measured car sections in [26]

3.2. Component-based Transfer Path Analysis

As a new transfer path analysis technique, Component-based TPA facilitates early detection of potential NVH issues and system optimization at the early design stage [29]. This method characterizes a noise source component (e.g. by means of blocked forces or free velocities) independently from the receiver structure, therefore allowing prediction of its behavior when coupled with different receivers. These sets of equivalent forces or velocities are an inherent property of the active component itself, and the forces can be applied to the FRFs of an assembled system with the active part shut down [25]. Furthermore, characterized components can be combined with either test-based or simulation-based components for assembly performance predictions at various stages of the product development cycle (Figure 6 [29]).

Both the classical and component based TPA are costly methods if used only to identify the dominant path contributions (especially between multiple incoherent vibration sources) in the assembled product. As introduced in Figure 4, transmissibility-based TPA methods can conveniently serve the same purpose. These potentially less accurate methodologies are easy to set up, versatile concerning sensor type and particularly effective for ranking contributions from several sources [25]. The reason for this method's lower accuracy is avoiding explicit force determination, ignoring complex interactions between components, and dependency upon the choice of indicator points around sources or connections which may leave out certain transmission path.

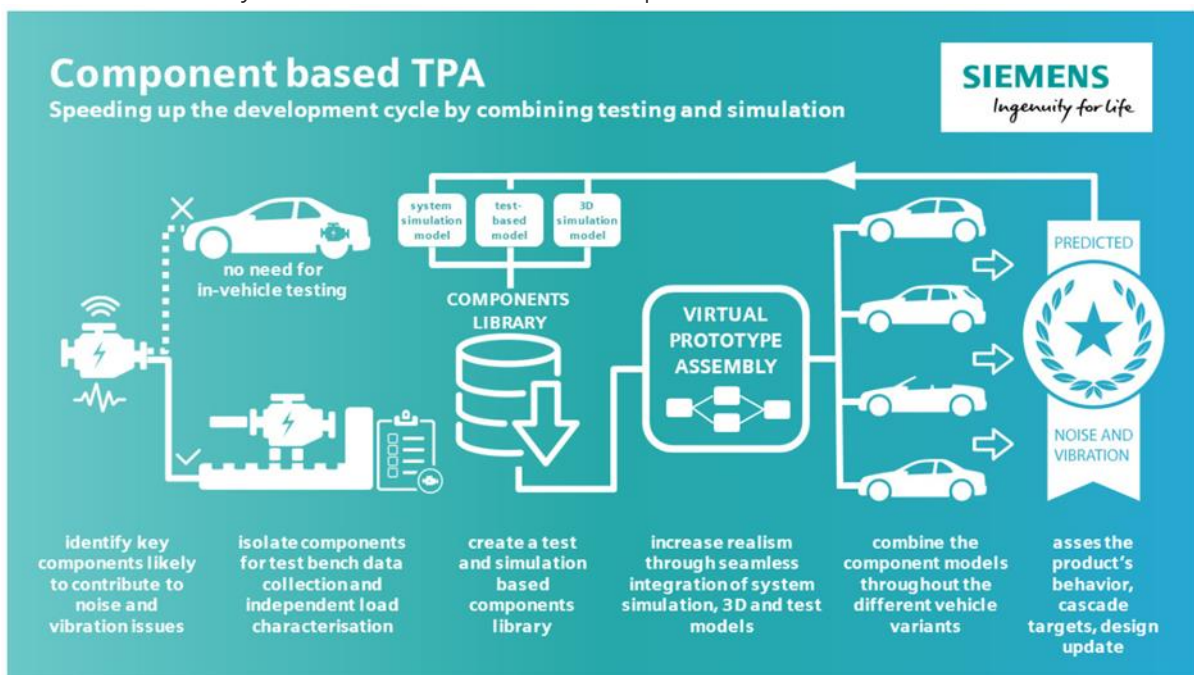


Figure 6. The concept of component-based TPA method [29]

3.3. Transfer Path Analysis using Dynamic Substructuring

Most TPA methods require the admittance of either the source, receiver or assembled structure. Dynamic Substructuring (DS) techniques are particularly useful for this purpose, as they allow us to assemble systems from the dynamics of its substructure. Component Mode Synthesis (CMS) and model

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reduction emerged in the 1960s as the first application of DS. The introduction of Frequency Based Substructuring (FBS), methods became available to assemble multiple substructures from FRFs, either obtained from numerical modelling or admittance tests. In fact, DS theory appeared very convenient to derive hybrid numerical/experimental TPA schemes and perform component optimization [25].

3.4. Panel Acoustic Contribution Analysis

Panel Acoustic Contribution Analysis (PACA) refers to a numerical technique to account for the contribution of vibrating structures in contact with acoustic domains. In reference [30], PACA is described in terms of ATVs. These relate normal velocities of structural components with pressure at a given observer point. This definition can be extended to other numerical methodologies in which an admittance matrix between normal structural velocities and pressures are defined [31]. The pressure contribution of each structure can be ranked [32], accounting for the most relevant components' contributors of noise.

4. Cabin noise simulation

Cabin noise is an interior noise problem. It consists of a closed fluid domain surrounded by a boundary surface. Cabin noise simulation has innumerable application, a typical example is the determination of the acoustic pressure field in the interior of a car or an airplane due to vibration of car body or airplane fuselage. In the following, more details about these two applications are given.

4.1. Automotive application

To improve the interior noise performance, Computer-Aided Engineering (CAE) predictions have gained importance, especially in the early development stage when it is still possible to make changes without negatively affecting vehicle development time [33]. Different prediction techniques are available to improve acoustic design. However most have limited applicability and good selection needs to be made depending on the acoustic problem encountered.

To build a broader understanding of vehicle NVH development, some basic concepts are given in the beginning of this section. As starting point, different noise sources on vehicles are showed in Figure 7 [34].

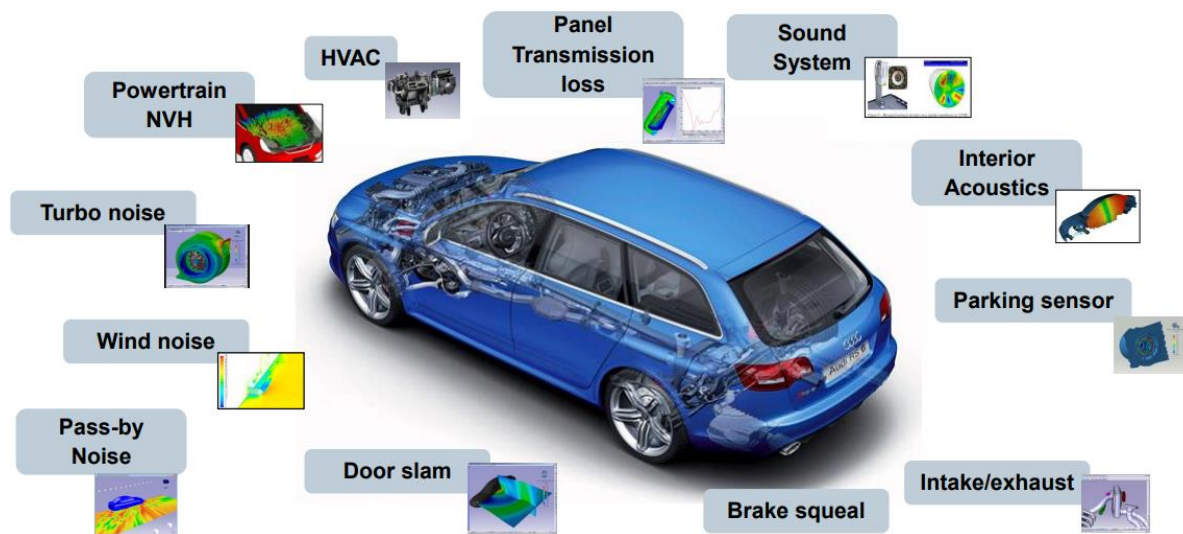


Figure 7. Noise sources on a vehicle [34]

The frequency spectrum of each source is also a valuable information for NVH engineers. A simplified representation of frequency content can be found in Figure 8 [34]. This gives a first indication about the numeric method suitable for each problem.

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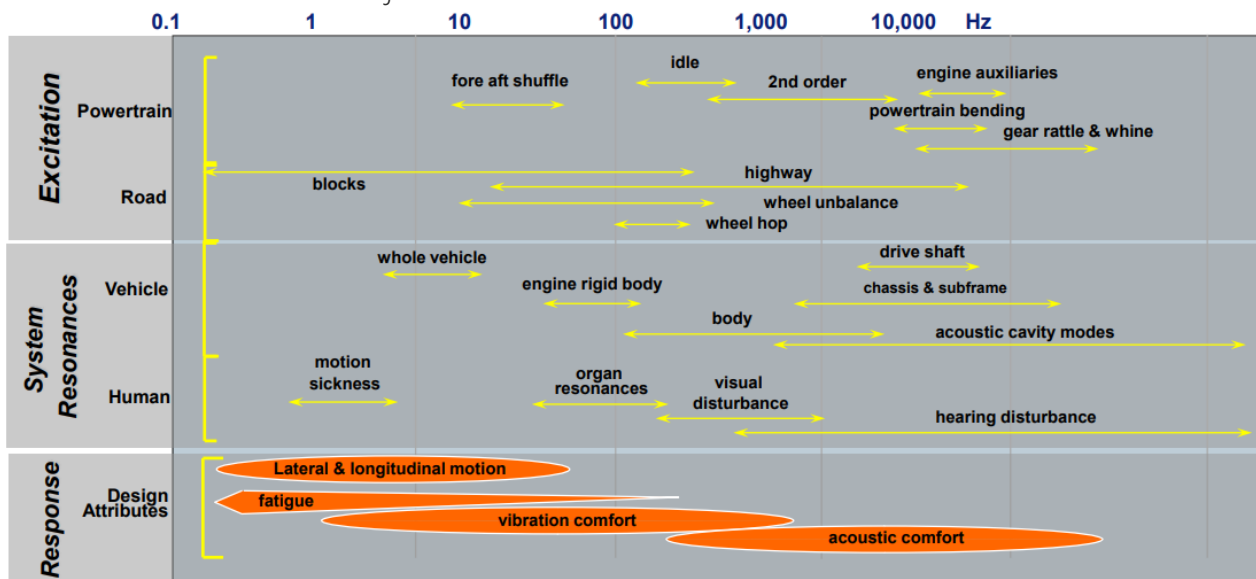


Figure 8. Summary of frequency component contribution to vehicle NVH and human perception of an internal combustion engine vehicle [34]

The use of CAE is also phase dependent since previous information and/or geometry models are necessary. CAE approach can be classified in three phases in vehicle development [38]:

- Concept phase: Computer-Aided Design (CAD) is not always available and CAE models are used to define the best design conceptually based on engineering expertise and simplified models.
- Detailed Engineering: usually CAD is available and refined models can be created. Design changes are evaluated for different performance attributes. Interactive process occurs to overall optimization of the vehicle. Full vehicle model depends on the creation of all subassemblies trending to be available last.
- Refinement Engineering: design validation and optimization phase. Design is fixed and test results became available on first prototypes. CAE is used to efficiently build component, subsystem and full-vehicle models. Inputs from test (loads, hybrid test-CAE approach) are used. Issues are identified and solved by alternative designs.

The concept phase has an important role in the development cycle since solving issues in the start of the project can be beneficial in terms of cost and time. To reduce project time, some components rely on fully CAE-driven approach [39]. For example, vehicle body-in-white (BiW) typically has its design frozen early in the project because other components rely on its design. Modification in BiW is difficult to manage and implement in later phases. On the other hand, if you have an NVH issue related to the body it is hard to solve in the refinement phase.

According to [5], the main analysis and CAE deliverables on vehicle noise and vibration refinement phase are:

- Vehicle modal alignment: ensure that the modes of different components are not matching frequency-wise to avoid any important resonance under operating conditions.
- Vehicle sensitivity transfer function:

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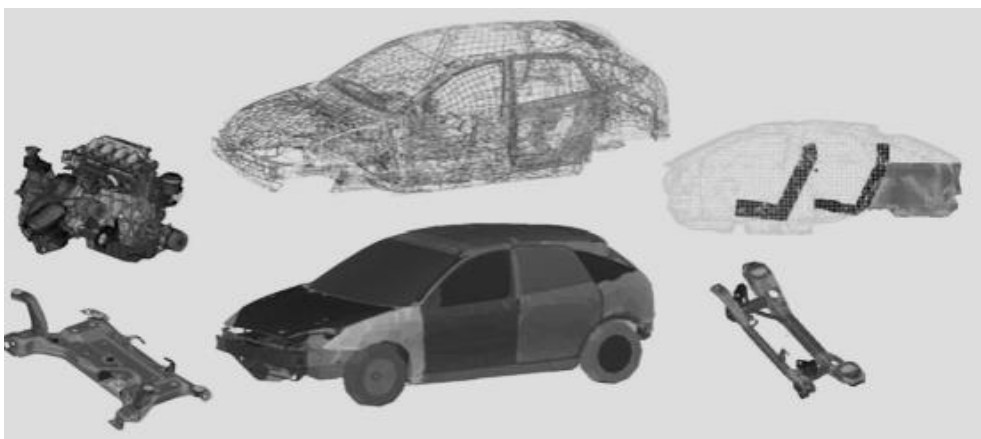
- vibration transfer function (vehicle response at the customer perception point due to, e.g., unit mount force, calculated by FE tools).
- noise transfer function (pressure/force, also calculated by FE tools) or
- noise reduction (sound pressure difference between engine bay and passenger cabin, calculated by SEA tools).
- Vehicle response to typical load cases:
 - “structure-borne response to idle excitation (loads of the powertrain applied to a full vehicle FE model).
 - response to wheel imbalance (nibble, solved by FE or system dynamics tools depending on vehicle content for electronic tools to reduce steering wheel rotation – EPAS).
 - response to road excitation or road noise (road surface irregularities applied to tire patch points using an FE tool).
 - vehicle acceleration noise (including all load paths in the TPA tool).
 - high-frequency noises like wind noise (derive the shape-related pressure fluctuation on the outer vehicle skin from CFD simulation and apply this as load for SEA analyses).”

In several situations the CAE models can be used to analyze individual components/sub-systems such as engine and electric motor. Often this approach enables to extend the frequency range of deterministic methods. It is then a common practice to cascade targets and requirements for each sub-system, simplifying the project of it [5], [35].

For cabin noise simulation, on the other hand, a full vehicle simulation is required. The size of the model can increase significantly as well as the modal density. FEM are typically used in lower frequencies while SEA and Raytracing are necessary to address higher frequencies. BEM is widely used for exterior sound radiation and transmission but for interior vehicle acoustics it is used less since FEM is typically more efficient [36], [37].

Up to this point an effort was made to shortly present the CAE framework inside NVH vehicle project. The following paragraphs present further details on interior acoustic and vibro-acoustic simulation using specific publications to showcase applications and experimental validation of the models.

Typical full vehicle simulation is done with the structural trimmed body coupled with acoustic cabin. An example of a CAE model can be seen in Figure 9.



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Figure 9. Finite element based full vehicle noise and vibration CAE model of Ford Focus and its main superelements: trimmed body, interior cavities, rear and front suspension subframe and powertrain [5]

A full vehicle model can include structure-borne and airborne paths. An example of a model used to calculate the transfer function between engine and pressure on passenger ears is shown in Figure 10. It is important to notice that it is possible to include panels and porous materials. The shown model is used to simulate the influence of a firewall with and without trim [40].

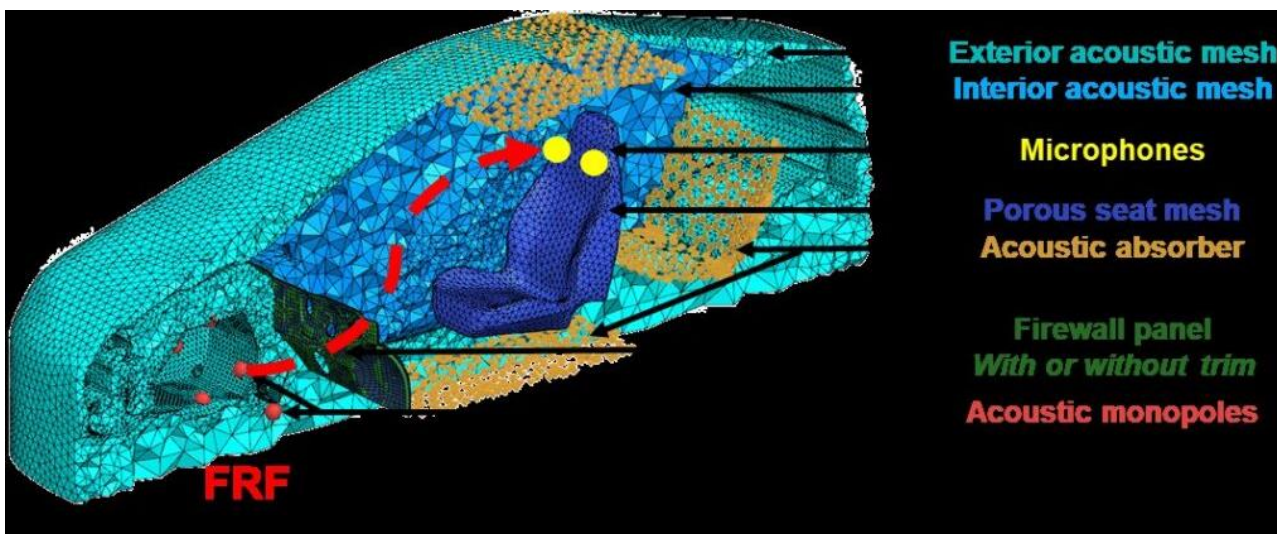


Figure 10. Full vehicle vibro-acoustic simulation model [40]

The experimental validation of the simulation is shown in Figure 11. The trimming of the panel has a significant influence on the analysis and a good validation is reached up to 11kHz.

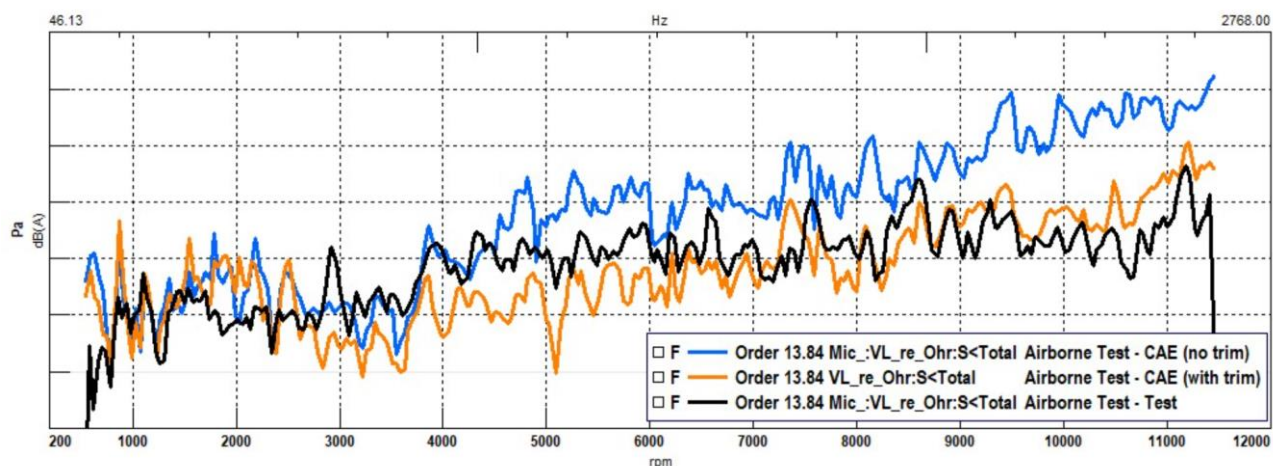


Figure 11. Interior noise prediction with and without trim for the right ear microphone position [40]

A full framework to develop a full vibro-acoustic model is described in [37]. Experimental validation steps are taken to validate the creation of the model step-by-step. First it starts by analyzing the acoustic cavity with rigid walls. Adding components such as roof trim, seats, panels, dashboard and floor carpet, one at a time updating cavity geometry and absorption properties of the numeric model. This approach enables to define where more refinement of the model is needed and trade-off between model complexity and accuracy can be defined.

Similarly, each structural component is also validated separately. The workflow starts by checking geometry of manufactured component and properties such as density and Young modulus. The experimental/numeric validation is done in three levels, only framed component, semi equipped component, and trimmed component. The Modal Assurance Criterion (MAC) is used in this verification. The assembled model started with “free” BiW and subsequently other components were added to reach the whole vehicle model. Only junctions where updated at this phase since components where already validated.

The full vibro-acoustic model is validated through a set of FRFs and by a subjective evaluation comparing a synthesized sound (using the FEM model) and a fully measured sound. The model and one FRF are shown in Figure 12. This model is dedicated to low frequencies (up to 200Hz).

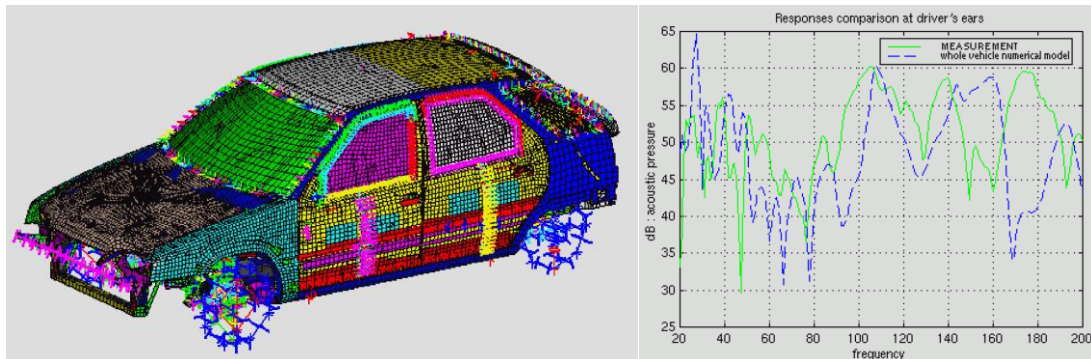


Figure 12. Left: the full vehicle trimmed FEM model with internal cavity. Right: the validation FRF between engine excitation and passenger ear [37]

Another relevant topic is to identify the contribution of each panel to the internal radiation. A panel contribution analysis of a trimmed body B-segment sedan vehicle can be found in [35]. Noise transfer functions are calculated using a full vehicle trimmed vibro-acoustic model.

As mentioned before, SEA models are used for analyzing higher frequencies. The low frequency range on automotive application typically ranges from 10Hz to 250Hz, and high frequencies are considered above 500Hz [7]. Different frequency ranges can be considered depending on each application.

On a vehicle, SEA can include the structural components and trimmed components, such as panels. The geometric representation of a SEA model is usually named “topological model”, it includes surfaces,

volumes, and connections [41]. For complex systems, such as vehicles, the accuracy of an SEA mode is highly dependent on the representation and correct identification of the component energy-related parameters (e.g. for airborne analysis: transmission loss and absorption curve of a panel). An overview of vehicle SEA model development and its use for target cascading can be found in [41]. SEA models can be used to define an optimized acoustic package (absorbing materials, panel thickness, leakage parameters. etc.) and new studies can contribute to enabling such models in earlier phases in the project [42].

Hybrid FEM and SEA models can also be developed to calculate the full frequency range. An example is shown in [43], where structure-borne noise is simulated by FEM up to 1.5kHz and the airborne contribution is calculated by SEA up to 8kHz. A full vehicle model was used to improve the cabin noise generated by whines of the electric motor.

For audio system development, the CAE approach can be unique in some respect since different analysis are relevant. A review of vehicle cavity simulation methods for audio system development is given in [44], including the ray acoustic models for high frequencies.

To conclude, the electrification of vehicles is a strong trend in the automotive industry. However, it changed important aspects of NVH analyses. The internal combustion engine, that was a primary source, does not mask other sources anymore. New components, such as electric motor (EM) and battery packs, changed the excitation and dynamic response characteristics of the vehicle. Numerical models to predict higher frequencies (from EM, wind, and road noise) and focusing on new components contributions are being developed worldwide. New types of analysis are key to differentiate a vehicle in a highly competitive market and CAE is a powerful tool to optimize the vehicle.

4.2. Aerospace application

In the recent years, some advances have been made regarding simulation of interior noise of aircraft cabins. The simulation schemes change depending on the frequency range, determining which kind of method (either deterministic or stochastic) is more suitable for the noise excitations.

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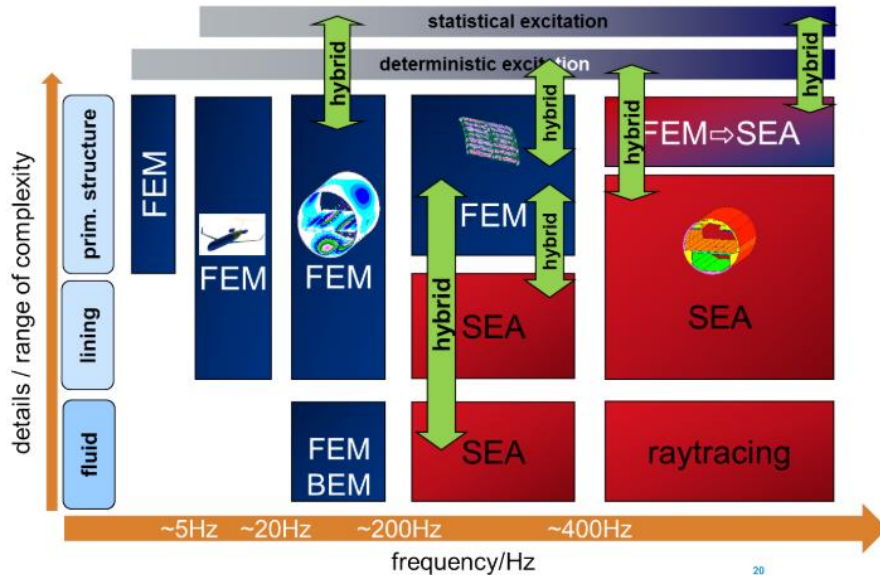


Figure 13. Simulations strategies in the aerospace context [13]

The main criteria that defines which method is more effective, relies on the Helmholtz number. This number represents the ratio of geometrical dimension L and wavelength λ : $He = L/\lambda$. When the wavelength is in the order of magnitude of the system, the overall behavior is deterministic, meaning that small changes don't lead to different responses [13].

As one can observe in Figure 13, the simulation methods are well divided in the frequency range, being FEM and BEM the most suitable methods in low-frequency range. As it was explained in the beginning of this document, FEM and BEM are deterministic methods that can reproduce very complex models. But this accuracy does not come at any cost, since the computational requirements increase with the frequency, as the number of elements strongly rise at higher frequencies.

At the same time, the accuracy of SEA decreases at low frequencies, where the behavior of the system is deterministic. As mentioned at the beginning of this document, the advantages of SEA depend on the high efficiency of the equation solver. This is because it is a meshless method, and it only requires the computation of the energy flows between the components of the system.

Simulation cases of aircrafts can be found in the literature, where different strategies (either deterministic or stochastic) are used. In [45], Statistical Energy Analysis is performed on a section of an aircraft on the range between 1kHz and 10kHz studying different configurations. In [46] the Boundary Element Method is used to predict the noise inside the cabin at specific locations near the headrests of the seats, and an experimental validation is performed. In [47] a Finite Element Model for vibro-acoustic analysis and cabin noise prediction is studied to assess different fuselage configurations in terms of material.

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In simulating aircraft cabin noise, it is not possible to use only one type of method, since the noise sources span from the low to high-frequency ranges. Attending to the noise sources, aircrafts can be subject to the following loads [48]:

- Turbulent Boundary Layer (TBL): this source of noise is stochastic and broadband, and it is generated by the pressure fluctuations at the surface of the fuselage. It is quite often the most significant source of noise in cabin during flight conditions. The frequency range spans from low to high frequencies.
- Propeller noise: this source is deterministic because it depends on the rotational speed of the propeller. The largest tone corresponds to the *blade-passage* frequency, which normally is a low or mid-frequency tone. On top of it, there is a TBL noise due to the airflow on the blades.
- Engine noise: this source is non-deterministic, and it is due to the TBL from the nozzle of the engine. As the TBL noise, it can span from low to high frequencies.
- Structure-borne noise: this source is deterministic, and it is associated to the unbalance of rotating parts of the propulsion systems of the aircraft. It is a low-frequency excitation.
- Other sources of cabin noise: ventilation systems and other mechanisms of the aircraft.

The distribution of these sources variate, not only in frequency, but also in space. In Figure 14 the spatial contributions can be observed.



Figure 14. Sources of interior noise prediction [13]

In [13], a workflow to study the full frequency vibro-acoustic behavior of an aircraft is presented. Some of the main issues found by the author are the following:

- There is not a full digital workflow to study the whole frequency range, since software are specialized in CFD, FEM, BEM, or SEA, and they cover only 50-70% of the workflow of Figure 13.

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- Many solvers only master CFD and FEM independently, meaning that the process of retrieving the external airborne (TBL, engines...) loads from simulation must be done beforehand.
- Fluid-structure coupling, based on modal coupling and dynamic sub-structuring, are not implemented for vibro-acoustic phenomena and in some cases, it is not applicable.
- Digital modelling incompatibilities between FEM and SEA.

The author also states that preparing the model takes the 90% of the modelling time, with respect to 10% to perform the simulation. This pulls the efforts towards creating a robust digital modelling framework, that generate automatically and adequately the models.

In the recent years, efforts have been made to create a unified digital modelling scheme for aircrafts, called CPACS (Common Parametric Aircraft Configuration Schema) [49]. This scheme has been in constant development, and last contributions are in terms of vibro-acoustic low-frequency noise [50]. Current developments in DLR internal project INTONATE [50] go on the direction of setting a simulation scheme for the study of noise inside the aircraft cabin by means of the Finite Element Model approach for the low-frequency range.

In summary, the simulation of noise in cabins of aircrafts can be challenging due to the lack of unified methods and workflows. The different transmission mechanisms, the nature of the acoustic loads, and the variability of aircraft parts and models, make the current framework to be weak and inefficient. There is clearly a need to unify a process of aircraft modelling (with promising projects as CPACS), and simulation schemes of low-frequency (FEM/BEM), mid-frequency (hybrid FEM-SEA) and high-frequency (SEA) loads, that flexibly could adapt the models to the requirements of the specific solver. At the same time, computational and memory requirements are critical in simulating large aircraft models, and for that it is necessary to implement methodologies that could strongly reduce these efforts (for example, modal reduction methods, substructuring, adaptive meshing...).

5. Future research

To extend the application of acoustic and vibroacoustic simulations to different industries, still important challenges have to be overcome. This section discusses the challenges for NVH simulation of car cabins and airplanes. Finally, possible contributions addressing these issues in the framework of IN-NOVA project are mentioned.

5.1. Acoustic simulation challenges

The improvement of computation power and emergence of new methods and technologies have enabled the enormous growth of numerical methods. At the early ages of developing numerical methods, many simplifications had to be made to be able to solve the real system under reasonable time durations. Thanks to the progresses in numerical computations and in computer technology, more realistic and accurate models can nowadays be created. However, it is interesting to note that the following challenges still need to be tackled:

- Computational time: is a key parameter that can increase the frequency for which deterministic models can be applied, enable to increase complexity and accuracy of models, permit evaluation of more design proposals and/or decrease project time.
- Memory allocation for simulation: even with current computation power, the memory allocation can become a limiting factor as models grow in complexity, size and accuracy. As described, accurate vibroacoustic modeling of an aircraft tends to be limited by memory requirements.
- Accuracy: every model simplifies the real behavior to some extent. CAE models allow the representation of more complex systems compared to analytical models. To further optimize the product (sometime including details or new physics to the modeled), engineers need to increase accuracy. But many times, accuracy is application-dependent and comes with research and/or experience.
- Variability and uncertainties of real systems: uncertainties associated with manufacturing, material characteristics, boundary conditions applied on systems, the unpredictability of the environment, etc., need to be accounted for in vibroacoustic modeling of car cavities [51]. This uncertainty and variability's effect on vehicle's response become more important at higher frequencies [38]. These input uncertainties can cause large variability in the calculated pressure field in the vibro-acoustic domain.
- Pre-post processing time: preparing the model (including CAD simplification, meshing, parameter definition, etc.), and creating relevant analysis data is time consuming. The exchange of model data between low-frequency and high-frequency analyses is difficult, and there are no current workflows that tackle this problem. For aircraft simulation, modelling can take up to 90% of the time in some applications [13].
- Multi-physical design and optimization: the NVH modeling of complex designs is a challenge of its own. Considering cross-disciplinary targets (such as heat transfer, structural rigidity and fuel consumption, etc.) increases even more the complexity, and it is hard to understand the influence of each design feature on such targets.

5.2. Trends on vibro-acoustic simulation in automotive and aircraft industries

With regard to the computational time issue, different Model Order Reduction (MOR) and parametric MOR (pMOR) approaches are being developed. They enable real-time simulations and/or increase design variations. Further research is still needed to come up with new applications in the industry. The usage of MOR together with DS approaches is a powerful technique for reducing computation time and memory allocation. Also, simulation challenges are faced when trying to include the acoustic numerical model in a Digital Twin of a car. MOR is needed to allow virtual sensing methods to provide the full field pressure of a vibro-acoustic system in the time domain efficiently. In addition to stability, these MOR techniques need to maintain the high-fidelity property of the original model and provide an efficient and accurate prediction [52].

From experimental data it is easy to see the huge contribution of the variability and uncertainties in real products. The robustness of a solution is highly dependent on the mapping of the unknown, and the correct representation of it in numeric models is challenging. There is still research and improvements to be developed to correctly consider it in many application areas.

Deterministic FEM models offer useful results for NVH related problems. Given a straightforward approach for the modeling, they are dependent on physical properties of the system. Extending FEM models to higher frequencies is desirable but, as already mentioned, challenging. Hybrid models to close the mid-frequency gap between FEM and SEA and/or to explore the benefits of each model in a combined manner are also foreseen in different studies. Classical SEA methods are dependent on experimental evaluation to define the energy flow between components, and design changes may have important influence on the determined parameters. The development of methods to precisely determine SEA variables at an early stage could leverage its usage.

Artificial Intelligence (AI) and machine learning (ML) techniques are being successfully used in different areas (language, images, sound, etc.) where huge amounts of data are available. Its usage to enhance engineering analysis is promising but challenging. The non-interpretability of trained model and non-meaningful results (hallucination) need to be overcome. This topic has evolved over the recent years, and its application will continue to grow in all areas.

The other challenge is making NVH predictions available earlier in the design process. CAE is needed in the early development stage when it is still possible to make changes without negatively affecting vehicle development time [33]. A CAE model is also needed for studying the optimal source distribution of exciters and microphones for performing experimental acoustic modal analysis on a car's cabin [33]. Such a model should account for the challenges involved: (i) the high modal damping ration caused by highly overlapping acoustic modes and (ii) obtaining a sufficiently homogenous sound field by distributing many references around the car's cabin.

5.3. IN-NOVA contribution

In order to address the issues of large CPU and memory requirements of FEMs for vibro-acoustic simulation in aircrafts, Said Pedraza (DC9) will implement dynamic sub-structuring techniques and modal reduction methods to the aircraft model. In a nutshell, the following simulation challenges will be addressed:

- Reduction of memory requirements using Component Mode Synthesis
- Reduction of memory and CPU consumption using modal reduction methods for the aircraft cabin and for primary and secondary structures
- Study of the flows of noise using Numerical Transfer Path Analysis based on Component Mode Synthesis
- Study of the contribution of vibrating panels into the overall cabin noise through Panel Contribution Analysis.

Machine learning (ML) development in the recent years have enabled innovative and more complex relation mapping by data-driven approaches. A hybrid approach using standard simulation/experimental methods and ML technique will be researched by Andrey Hense (DC7) to improve analysis and simulation efficiency on electric vehicle vibroacoustic development. Accurate concept models for early phase analysis will be developed to understand relations between targets and design variables. The goal is to provide analysis tools to take correct project decisions from the start. The research addresses computational time, memory allocation and accuracy by developing well suited concept models for battery pack and vehicle body dynamic response evaluation by using substructuring and Component Mode Synthesis techniques. The ML trained model used as a surrogate model can be seen as a Model Order Reduction to decrease simulation time. Inverse ML analysis can improve optimization techniques with complex variable settings. Explainable AI will be investigated in the view of developing recommendation systems that suggest design modifications in a complex variables relation environment. It can reduce post processing times and improve engineering analysis.

In order to combine the passive and active treatments to reduce the interior noise of electric vehicles, accurate models are needed to also estimate the high-frequency noise. Mahdi Ahi (DC6) will look into the different detection methods for structure-borne and airborne noise in BEVs and HEVs. He will start with the vibroacoustic simulation of an experimental metamaterial panel that covers the opening of a reverberation chamber (KU Leuven soundbox). In doing so, he will also identify the sound transmission behavior of panels equipped with active resonators, and investigate innovative methods for their feasible vibroacoustic modeling. The NVH performance of his proposed passive/active treatments will also have to be evaluated according to other design factors, including weight, producibility, cost efficiency, etc.

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