

Hybrid 3D Sound Intensity Measurements and Simulations Applied to a Truck Rear Axle

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Abstract

This study presents a novel methodology for optimizing the acoustic performance of rotating machinery by combining scattered 3D sound intensity data with numerical simulations. The method is demonstrated on the rear axle of a truck. Using Scan&Paint 3D, sound intensity data is rapidly acquired over a large spatial area with the assistance of a 3D sound intensity probe and infrared stereo camera. The experimental data is then integrated into far-field radiation simulations, enabling detailed analysis of the acoustic behavior and accurate predictions of far-field sound radiation. This hybrid approach offers a significant advantage for assessing complex acoustic sources, allowing for quick and reliable evaluation of noise mitigation solutions.

Introduction

The optimization of acoustic performance in automotive engineering has become increasingly challenging. With the advent of electric vehicles (EVs), Noise, Vibration, and Harshness (NVH) characteristics change significantly. In traditional internal combustion engine (ICE) vehicles, the broadband noise from the engine often masks other – more tonal – acoustic emissions, such as gear noise. However, in EVs, in absence of the broadband noise from the ICE, tonal noise components dominate the vehicle’s noise characteristics. In EV’s, gear noise is an important tonal noise source but there are more: drive e-motors and their inverters, auxiliaries and their electric drives, all those can contribute significantly to the vehicles sound emission. All this increases the need for a deeper understanding of the acoustic outputs from different components and sub-systems.

Numerical simulation and experimental testing are commonly used in acoustic engineering analysis. Both approaches have proven value, each with unique strengths in the design process. However, these two methodologies are typically performed by separate teams, and the results are often compared late in the design stage. More complementary and synergistic possibilities that leverage the capabilities of both methodologies simultaneously exist, and one hybrid methodology is explored in this paper.

This study focuses on a hybrid methodology that integrates experimental measurements with numerical simulations to investigate the acoustic output of a truck’s rear axle under propelling and braking conditions. By employing Scan&Paint 3D [1] —a rapid sound intensity scanning method using a 3D probe and infrared stereo tracking camera—we captured detailed near-field acoustic data. The measurements were then used as inputs for the finite element (FE) simulation tool Actran, enabling the creation of a numerical model without the need for meshing or creating and validating a structural FE model to generate vibration data inputs. Additionally, relative phase

information between a fixed reference microphone and the scanning probe was used to enhance the simulations, thus ensuring a detailed characterization of the main radiating surfaces.

3D Sound Intensity

Sound intensity is a metric that indicates the amount of acoustic energy in a sound field [2]. It provides quantification of the acoustic emission and the direction of sound propagation. In the frequency domain, sound intensity is a vector defined as the real part of the product of sound pressure and acoustic particle velocity [2], i.e.

$$\mathbf{I}(\omega) = \frac{1}{2} \text{Re}\{p(\omega)\mathbf{u}(\omega)\}, \quad (1)$$

where $\mathbf{u}(\omega) = [u_x(\omega), u_y(\omega), u_z(\omega)]$. In practice, 3D sound intensity can be measured directly, without any approximation, by capturing sound pressure and three the three orthogonal particle velocity components with dedicated sensors, a 4-channel probe, as shown in Figure 1.

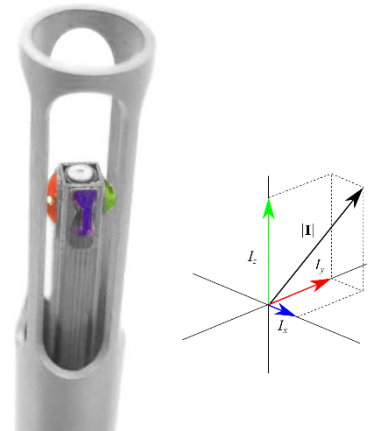


Figure 1: Sound intensity 3D probe, including a sound pressure microphone (top), and particle velocity sensors capturing components u_x (blue), u_y (red) and u_z (green)

Sound intensity measurements are beneficial for understanding complex acoustic phenomena and analyzing sound-related issues, such as sound source localization and quantification.

Measurement system

The Scan&Paint 3D solution was used for this investigation. The portable measurement tool capable of capturing and visualizing an acoustic field in three dimensions [2]. A 3D sound intensity probe captures information at a single point while an infrared stereo camera precisely tracks the probe's location and orientation with six degrees of freedom as it is moved along the measurement surface. During the capture process, the recorded signals and position in space are synchronized in real-time. A picture of the setup during the data acquisition phase is shown in Figure 2.



Figure 2. Scan&Paint 3D system used during the experimental testing campaign.

The sound field is then discretized using a cuboid grid over a 3D model of the object under test with a customizable spatial resolution that can be as fine as 3 mm. The direction (sound intensity and particle velocity vectors) and magnitude of the sound field can then be calculated using the discretized sound pressure and particle velocity signals [3].

Unlike traditional pressure-based methods, where intensity estimations are affected by the pressure-intensity index, the accuracy of a velocity-based probe is determined by the reactivity of the sound field [4]. This characteristic enables the system to perform reliable and accurate intensity measurements even in non-anechoic environments, such as the one investigated in this study. This flexibility offers a significant advantage when analyzing complex acoustic sources in environments that cannot easily be acoustically controlled.

Numerical Techniques for Acoustic Radiation

Actran is a commercial Finite Element software that can numerically solve acoustic problems in a variety of academic and industrial contexts. The most common computational analysis performed determines the harmonic response of an acoustic system by solving the following system of equations:

$$(\mathbf{K} + i\omega\mathbf{C} - \omega^2\mathbf{M})\mathbf{x}(\omega) = \mathbf{F}(\omega), \quad (2)$$

where the left-hand side is an impedance matrix, with \mathbf{K} stiffness, \mathbf{M} mass and \mathbf{C} damping, multiplied by an unknown, \mathbf{x} and the right-hand side a given excitation \mathbf{F} , as a function of pulsation $\omega = 2\pi f$ for any number of frequencies to be solved.

One of the most common use cases of this tool is to predict the free field (or semi-free field) sound radiation of a vibrating structure. In this

scenario, engineers have two main tasks to create their numerical simulation. First, they must create a finite element mesh and model, a well-understood procedure with industrially validated best practices [5]. Second, engineers must characterize the acoustic excitation, \mathbf{F} , coming from the vibrating structure. Historically, the most common way to compute \mathbf{F} was via another dynamic structure simulation. However, there is no limitation on characterizing \mathbf{F} via measurement data, such as a number of accelerometer positions or scan-based measurement systems.

BC Mesh method

Actran's Boundary Condition (BC) Mesh component allows engineers to easily apply previously captured vibration data as an excitation in the simulation model. This component can convert harmonic structural displacement, velocity, or accelerations to acoustic pressure and particle velocity boundary conditions for the acoustic radiation model, as well as project this data from the structural input geometry/measurement probe to the acoustic mesh. The main assumption for this approach is that the coupling between the radiating fluid medium and the vibrating structure is weak, or one-way. In other words, the air does not add any significant mass or stiffness to the structure, which would impact how it vibrates. This assumption is well respected for air within a free field but incorrect for heavy fluids like water or closed acoustic cavities, which influence the structure vibration.

The software allows for direct use of data from a collection of measurement points. This method works by localizing nodes in the finite element BC Mesh surface to the measurement points via a smallest distance computation. The measured data can be 3D acoustic particle velocity, assuming a continuity of normal velocity at the structure air interface. The BC Mesh nodes are split into vibration patches per measurement position, with the caveat that the resolution of the simulation is limited by the number of measurement points. With more measured data, a more complete vibration pattern can be created on the BC mesh. This is a particular strength of coupling Actran with Scan&Paint 3D – since the scanning measurement technique can capture thousands of virtual measurement points in a matter of minutes. In contrast, due to hardware limitations, traditional measurements with structure-mounted accelerometers rarely have more than 64 measurement locations. More information on this process is available [6].

Application Case

This section presents experimental and simulation results for the rear axle of a truck, measured under stationary propelling and braking conditions on a non-anechoic test bench. Absolute scales are omitted for confidentiality reasons. The rear axle was chosen as a representative example of a truck noise source with a tonal character. The proposed hybrid workflow can be replicated for a wide range of components and subsystems, provided that the device under investigation can be operated in a stationary regime.

Experimental campaign

A sound intensity probe was manually moved approximately 1 to 5 cm from the surface of the device. Every recording consisted of approximately 2 minutes of data captured while scanning a particular section of the target device. Twenty-eight recordings were made, totaling 45 minutes of scanning measurements. The entire measurement campaign, including setup, data acquisition, and

disassembly, was completed in approximately 3 hours. The scanning paths during this experiment can be seen in Figure 3.

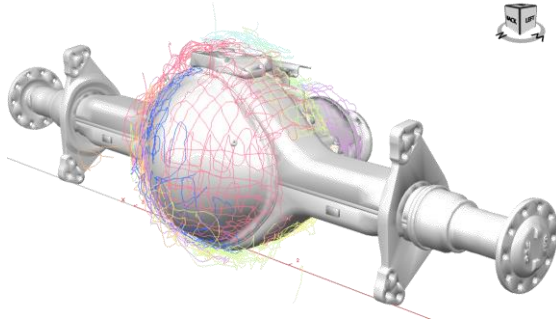


Figure 3. Measurement scanning paths.

The continuous scans were discretized during post-processing with a 20 mm grid resolution, yielding 1,850 and 1,900 data points for the propelling and braking operational conditions, respectively. The broadband 3D sound intensity results are shown in Figure 4, using a consistent color scale with a dynamic range of 20 dB for both vector maps. It should be noted that a decibel relative to full-scale (dBFS) was used for the sake of confidentiality. As shown, there are significant differences between the two conditions, mostly because the contact between the teeth of the pinion and crown gearwheels in the hypoid gearset changes depending on the torque direction.

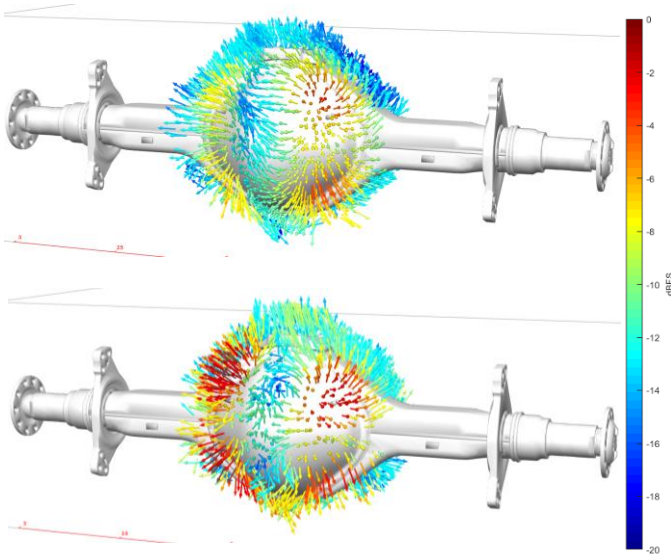


Figure 4. Broadband 3D sound intensity field visualized using Scan&Paint 3D during propelling (top) and braking (bottom) conditions.

Having detailed 3D sound intensity data enables us to perform a quantitative analysis to characterize the acoustic output of the device under test, as well as sub-component ranking. For this particular application, it was critical to understand how the sound radiation pattern behaves for the gear engagement frequency and its first harmonic. The figure below shows a comparison of the spatially averaged output for both conditions.

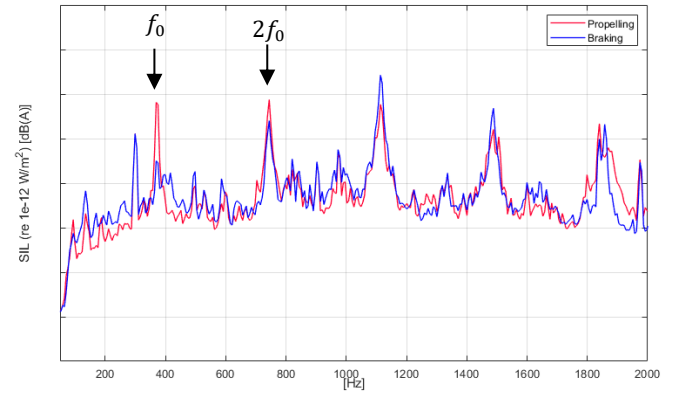


Figure 5. Spatially-averaged sound intensity around the rear-axle, highlighting the gear engagement frequency and its first harmonic.

Studying the narrowband sound radiation maps focused on each of the dominant frequencies can be key to finding the surfaces that contribute the most to sound radiation, as well as helping identify the underlying elements that cause vibro-acoustic excitation. Figure 6 displays the resulting sound intensity maps for the gear engagement frequency and its first harmonic.

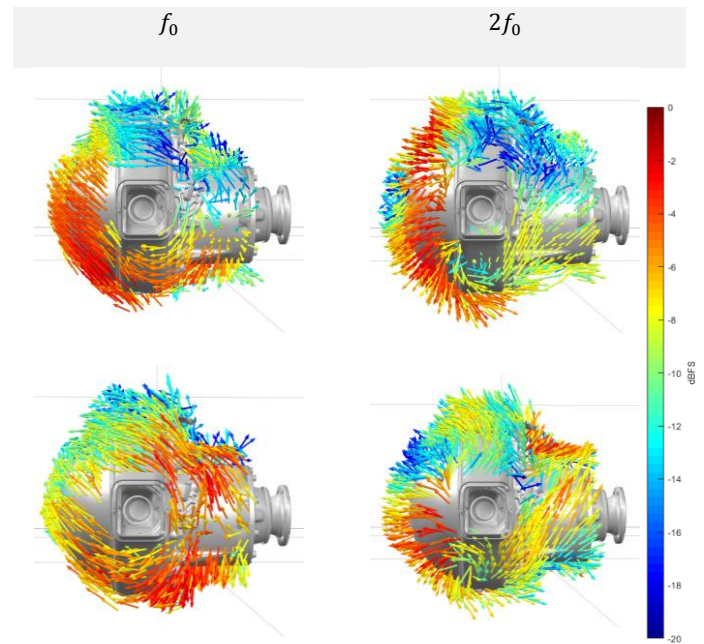


Figure 6. Narrowband 3D sound intensity maps focused on the fundamental gear engagement frequency and its first harmonic for propelling (top) and braking (bottom) conditions.

In addition, relative phase information was captured by placing a fixed microphone on the top side of the rear axle. Transfer functions between the fixed microphone and the moving probe were computed to extract the relative phase between them. This information is required for characterizing the operational deflection shapes. An example of the phase distribution is shown in Figure 7.

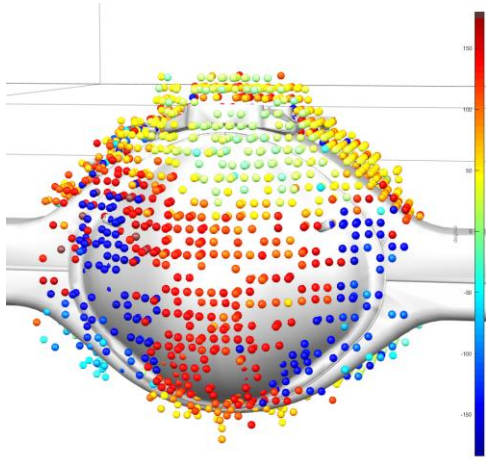


Figure 7. Relative phase information between a microphone located at the top side and the scanning probe for the fundamental gear engagement frequency.

Numerical simulations

The measurements from the experimental campaign detailed in the previous section were then used as input for a numerical analysis in Actran. More specifically, 3D particle velocity data combined with relative phase information towards the reference microphone was used. A simulation for the radiation of the rear-axle was performed using the BC mesh method and projecting the datapoints onto a FE mesh of the rear-axle captured during the Scan&Paint 3D scan and improved using Actran’s meshing capabilities.

To illustrate how simulations add value to the measurement data, the rear axle was placed “in-situ” on a computer-aided engineering (CAE) model of the actual vehicle and a shrinkwrap was generated to create a suitable analysis. A visualization of the final setup can be seen in Figure 8.

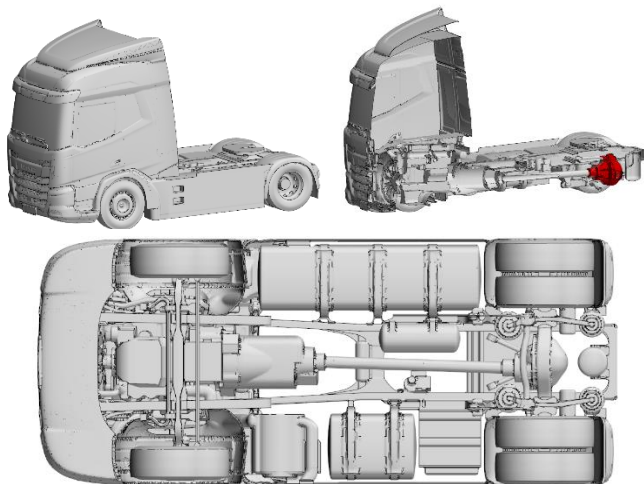


Figure 8. Actran simulation setup, including the vehicle shrinkwrap ISO view, a cut to the rear axle location, and a bottom up view.

One of the first simulated results to study is the radiated power by the rear axle in the two operating configurations, as per Figure 9.

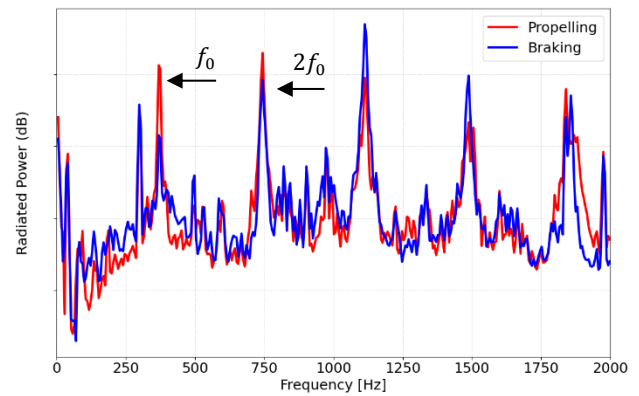


Figure 9. Power radiated by the rear axle, with peaks corroborating the measurement result.

As we expect, the simulation shows nearly the same tendencies as the measurement, with a first gear engagement peak in radiated power at 375Hz and a first harmonic at 750Hz. This provides confidence that the simulation is well built, that the measurement data was converted to an equivalent finite element excitation properly, and that the simulation results are accurate.

With the important resonance peaks identified, one can take advantage of the benefits of simulation when compared to measurement – namely that it produces complete knowledge of the system in the full simulated space – not just where detectors were present. Extending beyond the scope of the rear axle, propagation maps are plotted around the vehicle at the identified key frequencies to understand the most efficient noise propagation paths. At the fundamental rear axle gear engagement frequency, the propelling case radiates more power than the braking case, so the focus will be on the propelling case. It is observed that noise is loudest in the vicinity of the rear axle, underneath the vehicle where floor reflections amplify the noise, and on the back of the cab. The area ahead of the vehicle is relatively less noisy as the cab acts as an efficient acoustic barrier and most noise ahead of the vehicle comes from below the chassis.

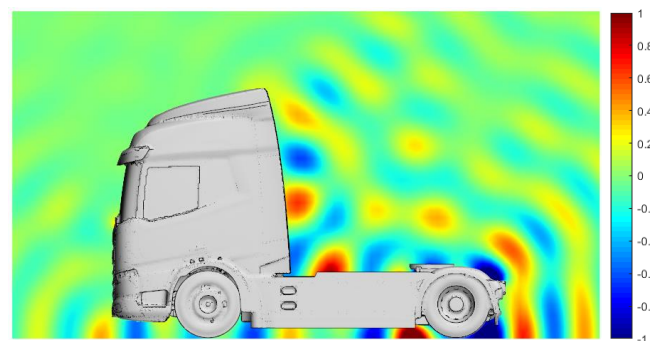


Figure 10. Propagation maps for the propelling case at 375Hz (normalized real part of pressure)

In addition to propagation maps, there are more advanced results that are achievable using the simulation. One of the important results for design engineers is the acoustic pressure on the exterior panels of the cabin. These can be output to serve as acoustic load structural excitations on a next step CAE model for determining the noise a passenger inside the vehicle would hear. In the simulation, the cabin exterior shrinkwrap was divided into 6 ‘panels’ that would excite the sides, front, back, floor and roof of the cabin.

The mean square pressure of each cabin panel can be plotted as an relative contribution, as seen in Figure 11. This allows for a quantitative ranking of which panel has the highest mean square pressure on it from the incident acoustic waves. The chart provides an indication of which panel is exposed to the highest average noise level, and which might be the most important to apply acoustic treatments to. Note that in this case the panel surface that had the highest mean square pressure as a percentage of the overall mean square pressure on all panels was the floor, followed by the back panel.

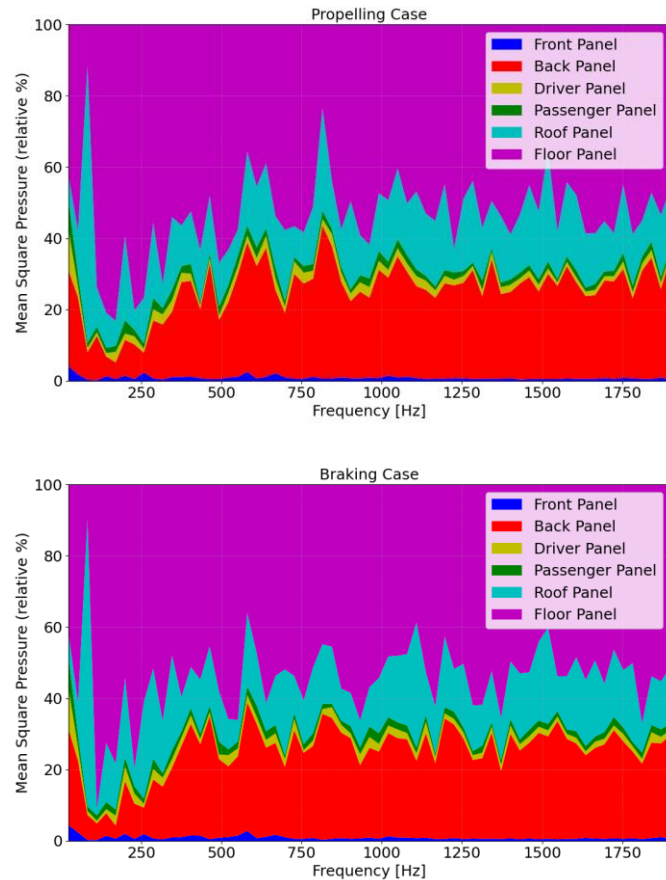


Figure 11. Relative mean square pressure of each of the 6 cabin panels during the propelling and braking conditions.

By combining knowledge of the gearbox engagement frequency peak with the panel mean square pressure ranking, it becomes formulaic to determine which panels and at which frequencies one should study to understand how to reduce noise in the cabin. In this case, the floor and back panels at 375Hz and higher harmonics can be mapped to understand where acoustic treatments could be placed for optimal efficiency. Of course, design constraints and the structural response of the cabin need to be considered as well for computing the final noise inside the cabin, but at this stage it is possible to understand where acoustic loading would be the greatest and where the design can potentially be improved. A suggestion based on the above reasoning can be seen in Figure 12.

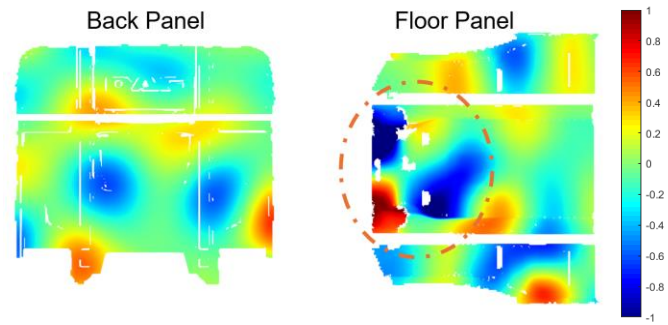


Figure 12. Back and rear panels for the propelling condition at gear engagement frequency of 375Hz. The region of highest acoustic load is highlighted as a suggestion for where the structure could be reinforced to limit noise in the cabin

With a structural FE model of the cabin, the evaluated numerical solution could be used to convert the above pressure maps into equivalent structural loads and couple to the structural modal solution as well as an interior air inside the truck cabin to determine Noise Transfer Function (NTFs) from the rear axle to passenger ear locations. Although outside the scope of this work, this is an industry-standard approach for classifying such NTFs and determining the acoustic comfort of the vehicle.

Conclusions

This paper proposes a hybrid analysis methodology that merges the strengths of acoustic measurements and simulations in the design process. Experimental measurements were conducted using a 3D sound intensity scanning technique to obtain spatially dense results in the near field of the component. The measurements were then used as inputs for advanced finite element (FE) simulation software, enabling the creation of a detailed numerical model.

The rear axle of a truck was investigated to demonstrate the effectiveness of this novel approach in understanding and optimizing the acoustic radiation of complex mechanical components at an early development stage. Experimental data showcased the sound radiation mechanisms linked to the gear engagement frequencies under propelling and braking conditions. The large amount of data available can be very useful for gaining a good understanding of the dominant surfaces and ranking their contributions. In addition, numerical results provide additional information regarding the operational deflection shapes and the surface vibro-acoustic behavior, which can be used directly to implement potential design changes and evaluate their performance in a fast and efficient way.

In summary, the proposed hybrid workflow is particularly useful in the late development stages of products, where acoustic issues may need to be addressed quickly. However, it can also be applied earlier in the development process when using supplied components with limited information on their acoustic performance. By integrating simulations and measurements, engineers can quickly gain a comprehensive understanding of complex acoustic dynamics and develop effective mitigation solutions.

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