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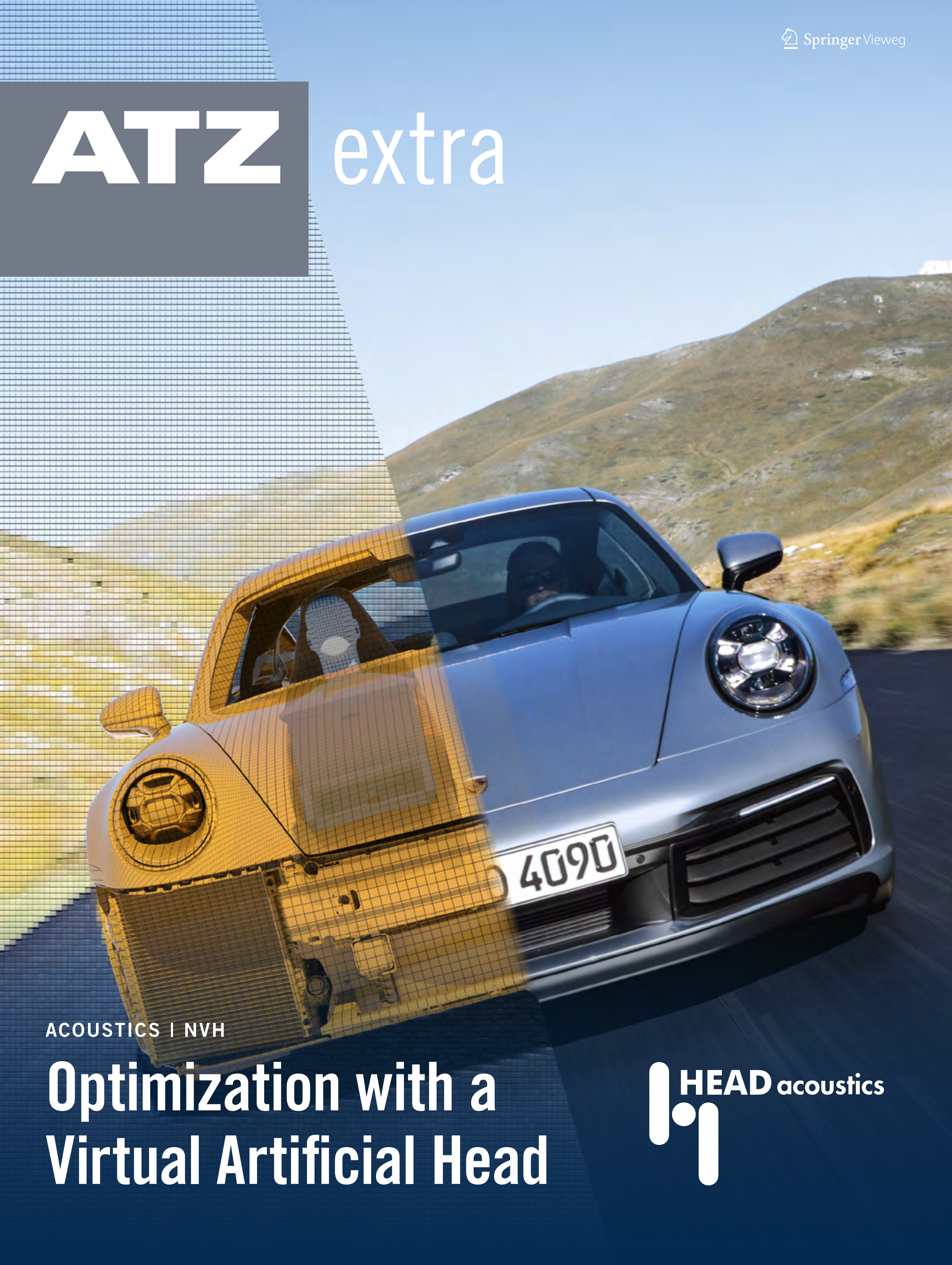
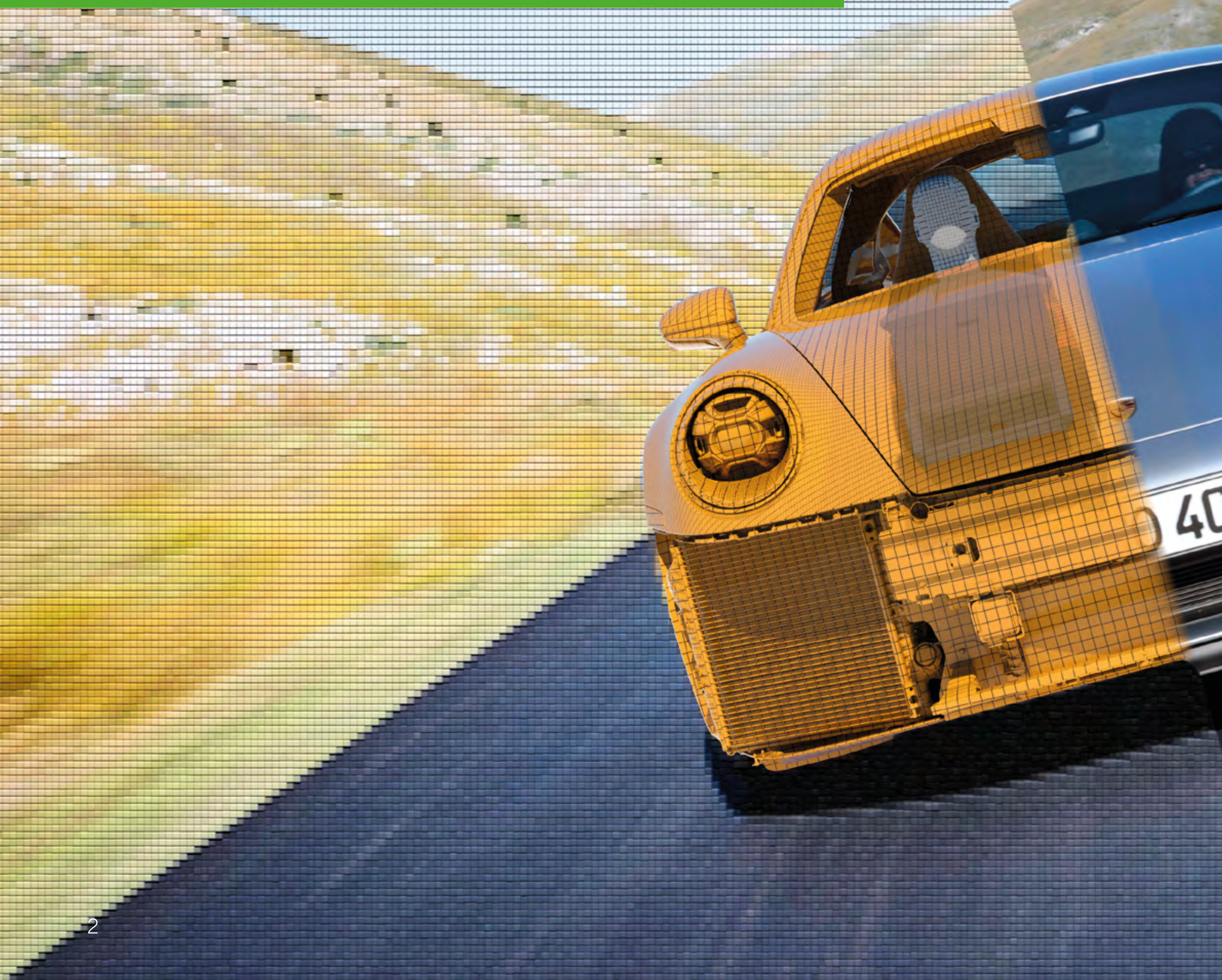


ACOUSTICS | NVH

Optimization with a Virtual Artificial Head

NVH Optimization with a Virtual Artificial Head

As developments take place in ever shorter times and with ever fewer physical prototypes, the acoustic properties of a vehicle under development are challenging to evaluate reliably. A realistic listening experience requires binaural artificial head recordings. Head acoustics and Porsche show how a virtual artificial head solves this problem.



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Simulations accelerate development, avoid cost-intensive corrections at a later stage of the development process, and, therefore, lead to a competitive advantage. With true-to-life simulations, nobody has to rely on abstract data with limited information about the actual experience: Tangible digital prototypes bring acoustic reality to the ears before it exists.

However, binaural artificial head recordings in physical prototypes are an essential component of the evaluation in NVH investigations. They enable a realistic listening experience and consequently make evaluations more reliable. A virtual – that means, simulated – artificial head is necessary to obtain comparably meaningful binaural simulation results.

The virtual artificial head factors in the diffraction effects caused by the head and shoulder, as well as the artificial head's influence on the sound field in the vehicle's interior cavity [1]. In this way, all participants experience

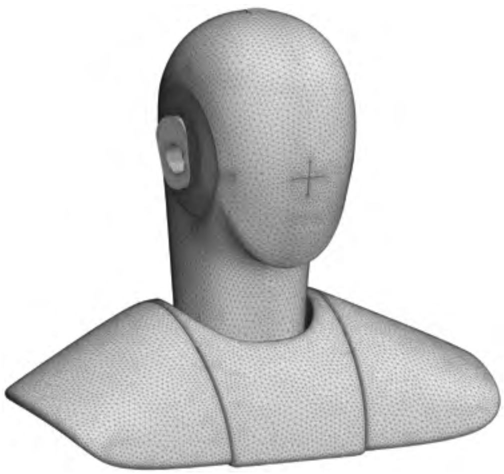

FIGURE 1 High-resolution finite element model of the HMS IV (© Head acoustics GmbH)

the realistic overall acoustic impression in the simulation even before manufacturing the first physical prototype.

VIRTUAL ARTIFICIAL HEAD MODEL

The HMS IV CAD model (4th generation Head Measurement System) is the virtual artificial head's basis. Based on the Finite Element (FE) method, a generated closed-surface model represents the surfaces of the externally visible components, **FIGURE 1** [2]. It is modular and, like the HMS IV, consists of simplified geometries of the shoulder, head, pinna, and external auditory canal. However, due to the complexity of the inner ear, the inner ear is not part of the consideration. As a result, the simulation results are expected to have a frequency limit below the limit of the human hearing range. The study scope comprises frequency range analyses up to 8 kHz. The model contains about 76.000 triangular elements with a mean edge length of 3 mm. Due to the proximity of the auricle and the external auditory canal to the microphone position and the small radii in this area, approximating the geometry at this location in detail requires using much smaller elements. On the other hand, the model contains larger elements for large radii and flat areas such as the head and shoulder.

VALIDATION OF THE VIRTUAL ARTIFICIAL HEAD MODEL

The comparison of the Head Related Transfer Functions (HRTF) from measurement and simulation serves to validate the FE model.

The experimental setup in the anechoic chamber of the Institute of Hearing Technology and Acoustics at RWTH Aachen University consists of loudspeakers arranged on a vertically aligned semicircle [3]. At the center of the semicircle (reference point), a reference measurement is taken with a microphone. Then, the artificial head is positioned with the midpoint of the two ear positions in the reference point. The artificial head can be rotated around the vertical axis between measurements to obtain HRTFs for multiple spatial directions. The artificial head recordings related to the reference measurement constitute the HRTF. It is free from room influence and loudspeaker transmission characteristics. Furthermore, the exact nature of the source signal does not matter (sweep/noise) as long as it contains energy in the entire relevant frequency range.

Reciprocity is assumed for the simulation. Output nodes for sound pressure are defined at the loudspeaker positions, and spherical sources replace the microphones at the ear positions. Additional output nodes generate the data for all spatial directions with one simulation calculation. The reference sound pressure can be calculated analytically since ideal free-field conditions exist in this case. To obtain results comparable with the measurement, the simulated sound pressures are related to the analytically calculated reference sound pressure.

FIGURE 2 shows the measured HRTF of the left ear in comparison to the simulated HRTF in the polar diagram, exemplarily for 500 Hz, 3450 Hz, and 7650 Hz for the horizontal plane. Generally, the curves have a good qualitative and quantitative agreement, even in the higher frequency range. At 7650 Hz, a deviation in the shape of the lobe in the shadow of the head at the 260° azimuth angle is visible, which may be due in equal parts to inaccuracies in the measurement and the geometric modeling of the simulation model. Over the entire simulated frequency range of 50 to 8000 Hz, we find equally good agreements.

PREPARATION FOR USE IN THE VEHICLE MODEL

For using the virtual artificial head in the full vehicle model and the later comparison with test data, the existing

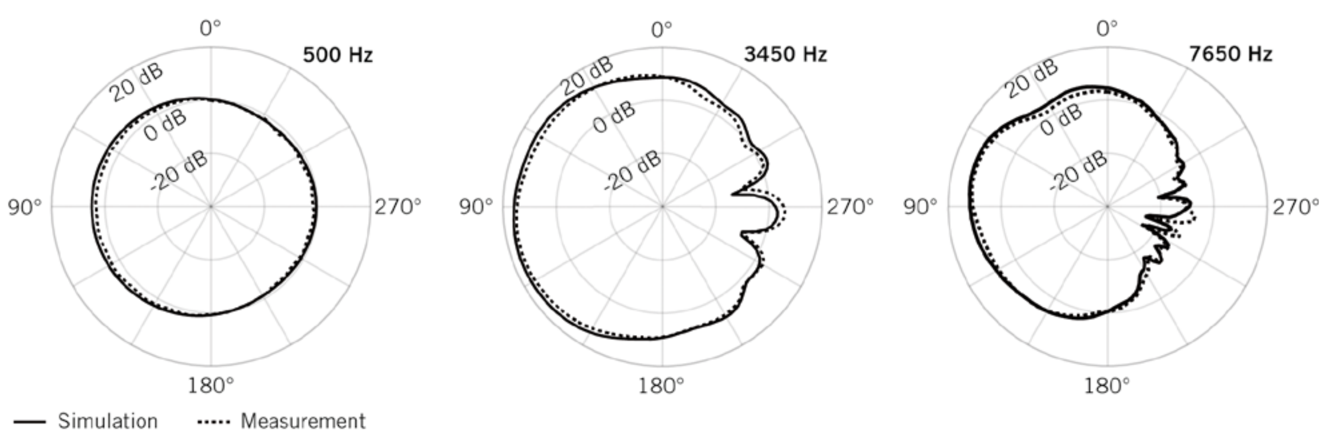

FIGURE 2 Comparison of measurement- and simulation-generated HRTFs in the polar diagram in the horizontal plane for the left ear for 500 Hz, 3450 Hz, and 7650 Hz (f.l.t.r.) (© Head acoustics GmbH)

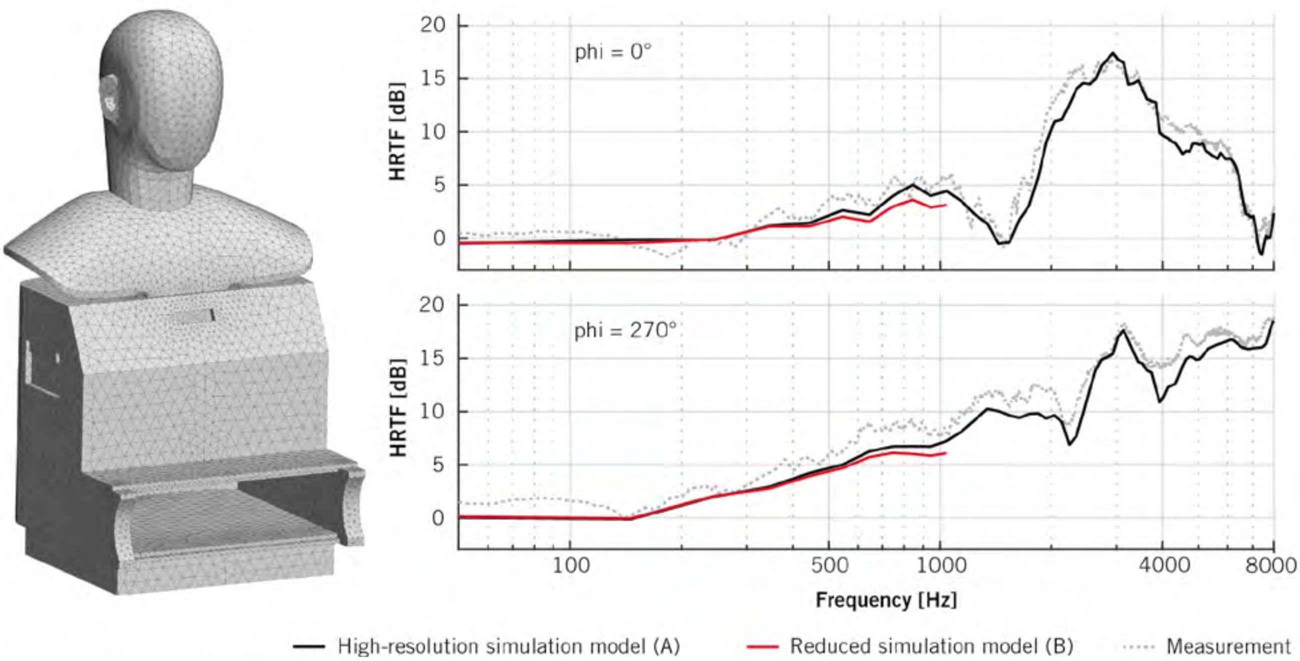

FIGURE 3 Reduced FE model of the Head and Torso Simulator and HRTFs of the right ear for the directions 0°/front and 270°/right: comparison of measurement, high-resolution, and reduced simulation model (© Head acoustics GmbH)

FE model is modified under certain constraints: it is extended by a torso box to represent the Head And Torso Simulator (HATS) [4]. Since the upper-frequency limit of the full vehicle model is about 1 kHz, one can model the FE mesh of the artificial head from much larger elements. A significantly smaller number of elements limits the overall vehicle model's complexity and increases the simulation computation's performance.

To realize the necessary coarser meshing, geometric simplifications of the artificial head model are required. The correspondingly modified FE model is shown in **FIGURE 3** (left). Despite the multiplication of the meshed surface by adding the (hollow) torso box, it consists of only about 20,360 elements. Compared to the original model of the head and shoulder, the most apparent geometric change can be seen in the closed collar. Due to the larger elements, the radii of the ears are approximated polygonally.

For the validation of the model, in **FIGURE 3**, we look exemplarily at the HATS-HRTF of the right ear for the directions phi = 0° (front) and phi = 270° (right) from the measurement compared to a high-resolution (A) and the reduced (B) simulation model. First, a good agreement of both simulation models with the measurement can be observed in general. Below 600 Hz, A and B provide nearly identical results. Above this frequency, acceptable deviations in the order of magnitude of those from the measurement to A occur due to the larger elements.

VEHICLE MODEL

To validate the use of the virtual artificial head in the vehicle model, various Acoustic Transfer Functions (ATFs) in the vehicle interior are measured and calculated for the Porsche 911 Carrera.

The ATF represents the ratio of the sound pressure (p) to the source strength (Q) (ATF = p / Q). The interior is excited using a standard sound source (monopole). The sound pressure is determined at the seat positions and the reference position near the sound sources (10 to 20 cm distance). Six different load cases are considered for the vehicle interior, each with differently positioned sound sources. The sound pressure at the driver's position is determined for each load case, once with a single microphone and once with an artificial head. The source and measurement positions in the vehicle interior are identical for the calculation and the test and are shown in **FIGURE 4**.

The simulative determination of the ATFs is carried out with an FE model consisting of a structural model (primarily metal components), the interior cavity, the acoustically effective insulating components, the so-called trim, and the interior paneling components (mainly made of plastic). The components are coupled with each other so that their feedback effects on each other are considered in the calculation.

The experiment determines ATFs in the fully equipped complete vehicle. The measurements are carried out on an acoustic test bench at the Porsche Development Center in Weissach to keep interference noise and reflections to a minimum.

VEHICLE MODEL VALIDATION

The current FE simulation models and the available hardware enable an upper frequency of 1000 Hz. In the test, the transfer functions can be evaluated from 30 Hz due to the signal-to-noise ratio. Thus, a comparison of the measured and calculated transfer functions is possible for the frequency range from 30 Hz to 1000 Hz.

We will discuss the comparison of load cases three and six in more detail

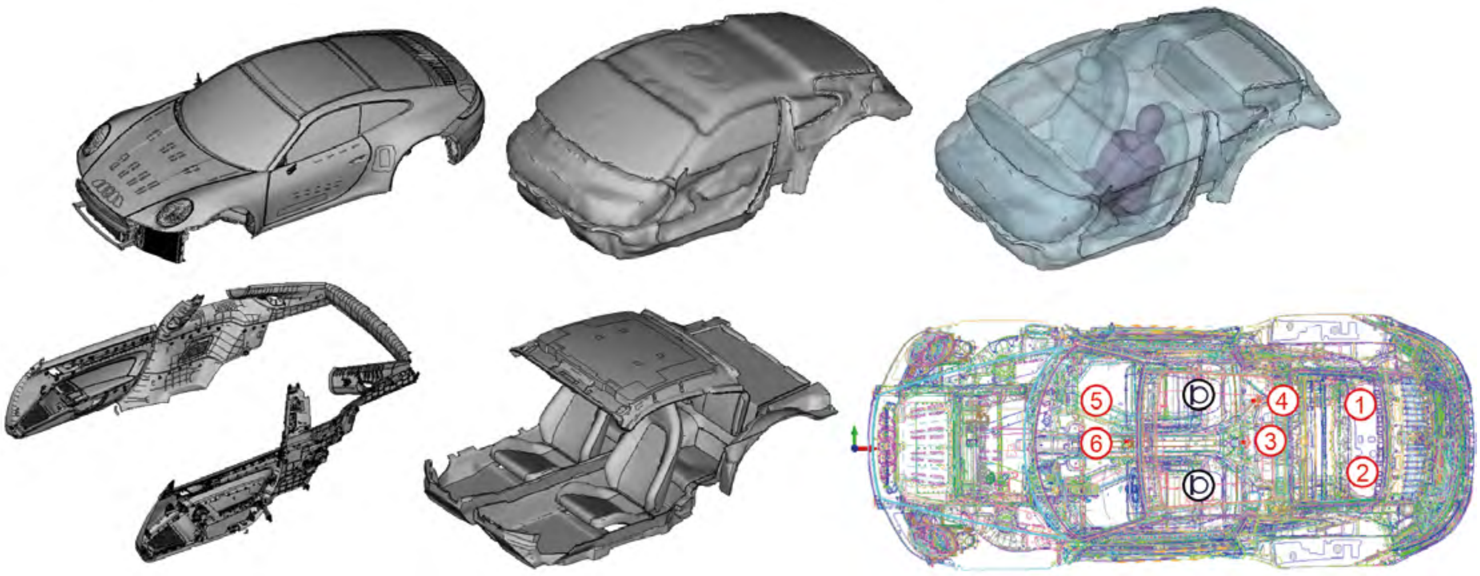

FIGURE 4 Representation of the simulation model consisting of structural model (top left), interior cavity (top center and right with artificial head), interior paneling parts (bottom left), and trim (bottom center). The excitation positions numbered according to the load case are marked in red, and the measurement positions are marked in black (bottom right) (© Dr. Ing. h.c. F. Porsche AG)

below. For each measurement position, a very good correlation between simulation and test is recognizable, **FIGURE 5**. The occasional deviations detected in the narrow band in the evaluation can be better classified using the third-octave band averaging common in acoustics. It thus becomes clear that there is also a satisfactory correlation between the test and the simulation for the higher frequency range.

To further illustrate the differences between the microphone and dummy head, in **FIGURE 6** (top), we compare the signal from the single microphone at the driver's position with the two signals from the dummy head in the third-octave band averaging. The comparison shows that the level difference in measurement and simulation is reproduced similarly over frequency. In both load cases, the airborne sound level at the artificial head's left ear is higher than the airborne sound level at the right ear and the single microphone between 200 Hz and 400 Hz. Above 400 Hz, the relationship is reversed, where the artificial head's right ear has the highest airborne sound level.

Using the virtual artificial head enables jury evaluations and the psychoacoustic evaluation of simulation results. For calculating loudness according to ECMA-418-2 [5], a time signal of 3 s of white noise is convolved with the transfer functions from simulation and measurement. By binaural combination, the loud-

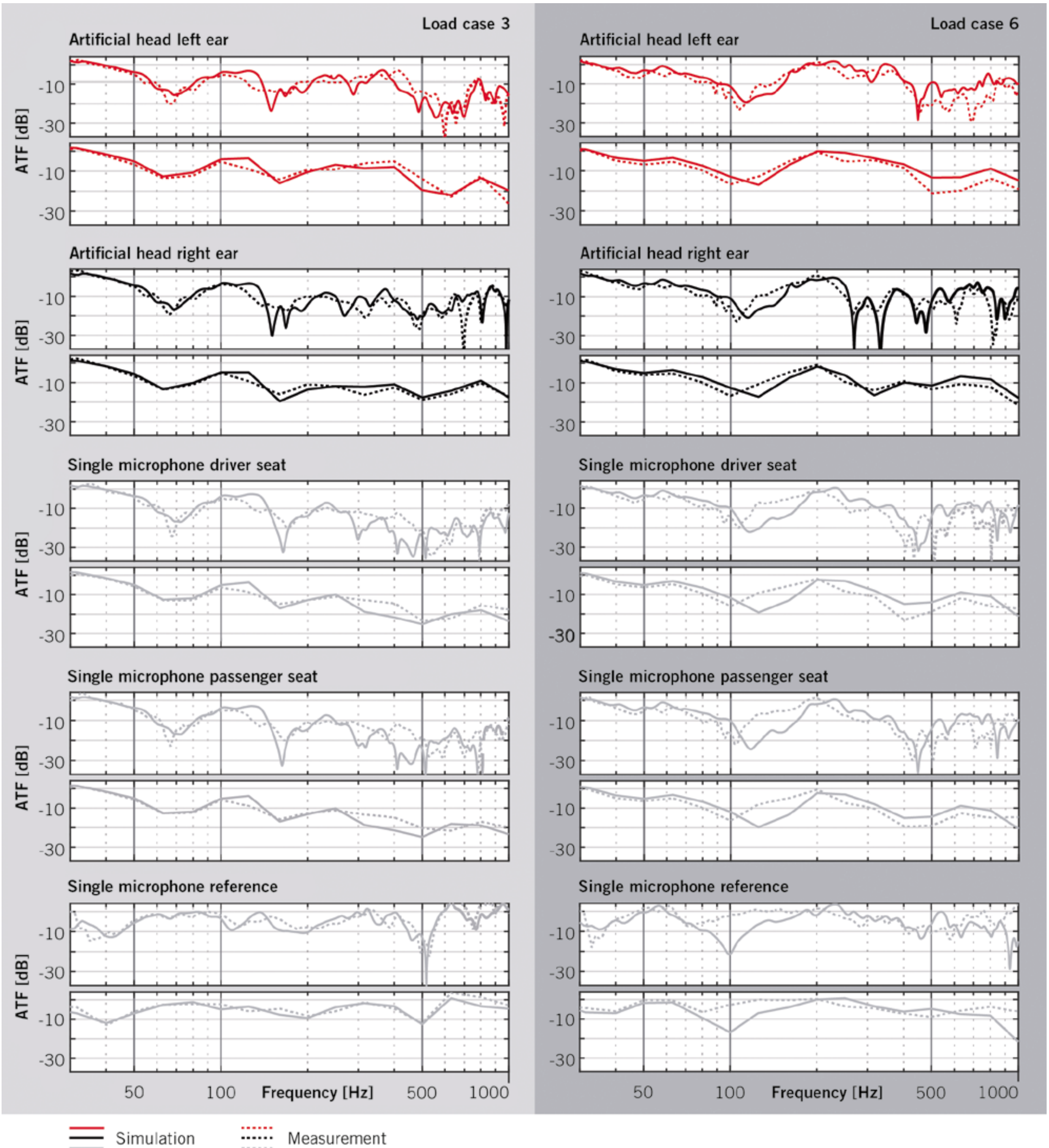

FIGURE 5 Comparison of measured and simulated Acoustic Transfer Functions (ATFs) in the narrow band and third octave band for load case 3 (left) and load case 6 (right) (© Head acoustics GmbH | Dr. Ing. h.c. F. Porsche AG)

ness calculation for the artificial head produces one curve that can be compared with the loudness curve for the single microphone, **FIGURE 6** (bottom). According to the standard, the loudness curve reaches an evaluable level starting at approximately 0,3 s. The correlation of the loudness ratings confirms the previous comparisons between simulation and measurement.

SUMMARY AND OUTLOOK

Artificial heads have been essential in NVH investigations for decades. At the same time, the number of physical prototypes is decreasing. Therefore, the next logical step leads to the virtual artificial head in corresponding simulation scenarios.

In the article, the described FE model of an artificial head is validated using metrologically determined head-related

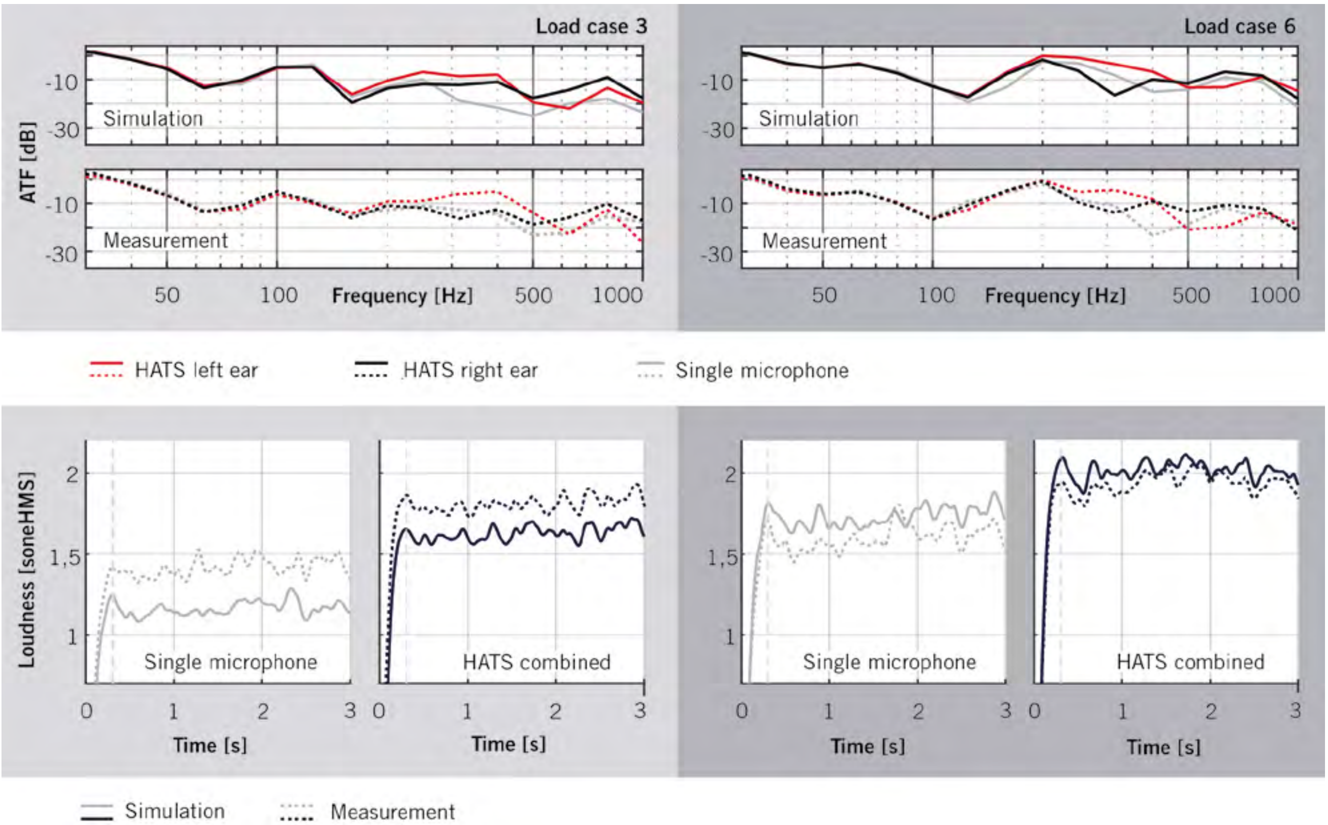

FIGURE 6 Top: Comparison of the sound pressure at the single microphone to the artificial head's ears for simulation and measurement in the third-octave band, load case 3 (left) and load case 6 (right). Bottom: Loudness rating comparison according to ECMA 418-2 between simulation and measurement for the single microphone and combined for the artificial head, load case 3 (left), and load case 6 (right) (© Head acoustics GmbH | Dr. Ing. h.c. F. Porsche AG)

transfer functions for the horizontal plane up to an upper-frequency limit of 8 kHz. This validated virtual artificial head model allows a realistic consideration of diffraction effects and the acoustic influence of the artificial head on its environment and serves as a surrogate model for the impact of a human passenger. At the same time, it ensures the comparability of simulations and measurements in the later course of development.

For the application in the vehicle model, the described artificial head model is extended by a torso box. When comparing the measured and calculated transfer functions in the complete vehicle, a very satisfactory agreement for the artificial head used can be shown.

The binaural simulation of the vehicle interior increases the quality of the results. It enables an evaluation of the realistic auditory experience at an early stage of product development and optimization that centers on human perception.

Simulated acoustic scenarios can be realized in different contexts. Decision-makers thus have a wide range of tools to make the necessary critical decisions early in the development process. The possible range of applications extends from binaural sound examples and the NVH desktop simulator to full vehicle simulators, such as the Porsche NVH-Lab or the mobile NVH simulator in the actual vehicle.

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