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Development of a Multiphysics Simultaneous Measurement and Visualizatiaion System for Wide-area Non-stationary Acoustic Phenomena

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Automotive acoustic environments are becoming increasingly complex as electrification reduces traditional masking noise and raises the perceptibility of low-frequency, transient, and other non-stationary acoustic components. As a result, modern vehicles are more sensitive to short-duration acoustic events originating from rapidly evolving flow and structural interactions. Conventional diagnostic techniques—particularly scanning-based sound field visualization—are fundamentally limited because they assume steady-state conditions and acquire spatial information sequentially, preventing them from preserving the temporal coherence of fast-changing phenomena or supporting synchronized multiphysics measurements. To address these limitations, this study introduces a multiphysics simultaneous measurement and visualization system designed to capture wide-area, highly transient acoustic fields encountered in real engineering environments.

The system centers on a newly developed 12-channel (12-CH) 3D Acoustic Vector Sensor (3D-AVS) array, the first of its kind worldwide. With 75-mm spacing and full 3D measurement of sound pressure and particle velocity, the array provides true single-shot acquisition of acoustic intensity vector fields. Because all channels are sampled simultaneously, the system avoids spatial–temporal aliasing inherent in scanning methods and accurately captures short-lived energy concentrations, transient radiation bursts, and rapidly evolving acoustic pathways. This capability is especially valuable in confined automotive spaces where scanning systems are impractical and rapid acoustic changes are common.

To support reliable multiphysics integration, the system employs a microsecond-level synchronization architecture. Multiple data acquisition modules—dedicated to the AVS array, thermal anemometers, and optional structural sensors—are connected to a common timing reference, enabling direct assessment of instantaneous causal relationships between internal flow dynamics and radiated noise. Such relationships cannot be obtained from traditional time-averaged or sequential approaches, making the system particularly effective for analyzing moment-to-moment aeroacoustic emission mechanisms. The synchronized dataset also avoids timing ambiguities that often complicate transient measurements in multi-sensor systems.

The system was validated using an automotive HVAC duct, a representative source of intermittent and spatially localized aeroacoustic noise. When airflow of 10–20 m/s was introduced, turbulent structures formed within curved duct regions, producing intermittent acoustic bursts. The AVS array captured these bursts with high temporal fidelity, and synchronized flow-velocity measurements showed strong alignment between rapid flow fluctuations and emitted sound. Time–frequency analysis confirmed that high-intensity acoustic emissions were concentrated in frequency bands associated with vortex shedding. Projecting 3D acoustic intensity vectors onto images of the duct geometry provided intuitive visualization of transient energy pathways and clarified when, where, and in which direction acoustic energy propagated.

The system also enabled detailed investigation of left-hand (LH) and right-hand (RH) HVAC duct asymmetry. Coherence analysis indicated that the RH duct exhibited stronger instantaneous coupling between flow-velocity fluctuations and radiated sound, consistent with flow measurements showing more frequent separation events due to its sharper curvature. These transient flow behaviors manifested directly as stronger and more intermittent acoustic emissions, offering a quantitative explanation for perceptual noise differences between the two ducts.

Overall, the proposed system provides a powerful diagnostic platform for analyzing transient and non-stationary acoustic phenomena. By enabling wide-area, time-synchronous measurement of acoustic, flow, and structural dynamics within a unified spatiotemporal framework, the system advances the understanding of complex noise-generation mechanisms and enhances the effectiveness of noise-source identification and countermeasure development for next-generation vehicles. Its ability to uncover previously inaccessible short-duration phenomena positions it as a critical tool for future NVH development in increasingly electrified and acoustically transparent vehicle architectures. By revealing how transient mechanisms evolve in real time, the system offers a new foundation for designing quieter vehicles based on a fundamentally deeper understanding of time-dependent acoustic behavior.

Moreover, the method enables engineers to directly contrast predicted and measured transient responses, accelerating the refinement of computational aeroacoustic models. Such integrated insight is essential for developing robust design strategies that address not only steady-state noise but also the fast, intermittent events that increasingly dominate the acoustic character of modern vehicles.

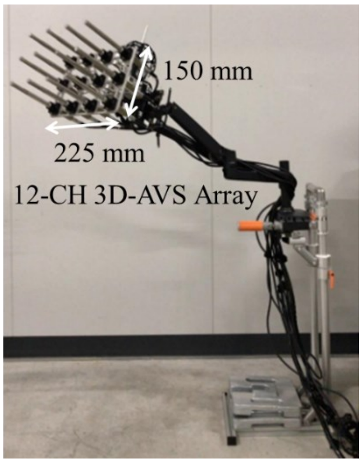

Fig. 1 Photograph of the 12-CH 3D-AVS Array