Wind Noise Challenge in Automobile Industry

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Abstract: Although automobile wind noise performance keeps improving, some fundamental aspects of wind noise generation and transmission paths remain uncertain. This paper raises issues to be solved in vehicle shape related wind noise root cause understanding and prevention. Wind noise mechanisms such as the generation of vehicle body wall pressure fluctuations (pseudo-noise) and their interaction with body structures, resulting in panel vibration, which radiates as noise, are described. Challenge issues such as the evaluation of the relative importance of low wave number versus convective contributions of pseudo-noise to structural excitation are discussed.

BACKGROUND

Aerodynamically generated noise perceived in the vehicle interior is of increased importance for automobiles as operating speeds increase and design improvements reduce noise contributions from the powertrain and road tire interaction. Wind noise reaches the interior through a variety of mechanisms including the aeroacoustic penetration and aerodynamic excitation of vibration and its radiation as sound from the vehicle greenhouse (roof, windshield, side glasses and backlight) and underbody. Vehicle design elements for low levels of wind noise include the vehicle body shape, appendix design, and seals design and manufacture. The importance of this latter element is well established, and the modeling of seal aspiration and seal noise transmission will be left to another occasion.

The flow disturbance of a moving vehicle generates turbulence which impinges on the vehicle greenhouse. Typical turbulent flows induced by vehicle body shape include the A-pillar vortices, side glass reattached flows, windshield/roof roof boundary layers and backlight separated flow. Wind noise is generated as the wall pressure fluctuations in these turbulent flow regions impinge on greenhouse body panels, causing panel vibration and radiating sound to the cabin. Vehicle appendages, such as mirrors, antenna, roof rack, etc., also generate regions of turbulence as well as affecting the mean flow about the vehicle. For example, the mirror vortex can generate turbulence which impinges on the side glass and may also modify the intensity and position of the A-pillar vortex, with dramatic effect on wind noise performance. In addition, mirror and antenna vortex shedding can acoustically excite vehicle body panels, radiating noise into the cabin.

The composition of vehicle body panels and sound package has significant influence on the wind noise perceived by the driver. By identifying transmission paths, wind noise can be reduced through body panel damping or sound package management. Her, et. al., experimentally identified contributions of various wind noise transmission paths including both body panels and underbody airborne sources (1). Their analysis and other recent measurements indicate that underbody contributions associated with turbulent flows in the wheel wells may dominate the wind noise spectrum measured in wind tunnel testing at low frequency. However, it is suspected that road and powertrain noise can overwhelm the contribution from underbody sources under road test conditions.

Automobile manufacturers are confident of their ability to evaluate prototype and production vehicle wind noise performance. However, the capability for accurate and detailed wind noise performance prediction before a prototype vehicle is constructed is desired in order to effectively modify vehicle design for wind noise performance in the early design stages. CAE tools have been developed to meet this demand. The remainder of this paper focuses on some challenge issues in advancing the development of these prediction tools.

CHALLENGE ISSUES

1. Root Cause Challenge — convective ridge, low wavenumber region or acoustic excitation? Unsteady aerodynamic pressures acting on and exciting the vehicle greenhouse panels is one of the dominant sources of interior noise during high speed cruise. The energy in the pressure fluctuations of turbulence around the vehicle can be characterized by their wavenumber-frequency spectra. The panel is excited due to the structure's modes integrating with the accepted wave lengths of the pressure fluctuations. There are three integration mechanisms that can cause panel vibrations: 1) the convective ridge of the wavenumber spectrum can drive the structure's modes (most likely off resonance), 2) the low wavenumber component of the spectrum may excite the structure at resonance, and 3) the acoustic pressure components of the spectrum can be transmitted through the non-resonant modal response of the structure.
An enhanced understanding of the actual wavenumber-frequency spectra of the spatially nonstationary flows experienced on the surface of an automobile and how those flows excite realistic panel structures is required.

2. Wind Noise CAE Prediction Challenge — direct numerical simulation. A successful numerical simulation of wind noise performance using CAE tools requires prediction of the unsteady flow field via CFD (computational fluid dynamics), and the structural response, most likely through a combination of FEA (finite element analysis) and SEA (statistical energy analysis). CFD is required to simulate the turbulent pressure fluctuations acting on the vehicle surface. A direct numerical simulation of the 3-D unsteady Navier Stokes equations is not presently feasible for Reynolds numbers of practical automotive interest. Steady forces might be computed reasonably well by a Reynolds-averaged solution of the Navier Stokes equations (RANS) incorporating an empirically derived turbulence model, however, the unsteady forces at mid to high frequency cannot be resolved by this technique. A LES (large eddy simulation) approach to the solution of the Navier Stokes equations, directly simulating the behavior of large scale motions of turbulence while empirically modeling the smaller, unresolved scales, provides a more practical alternative. However, the computational cost and present hardware capabilities (through both memory limitations and accumulation of truncation errors) presently limit the success of LES. A hybrid approach using measured turbulence data to "tune" LES calculations may prove and test the capability of LES further (2), however, such a process is not suitable as a design tool. Recently an unconventional approach to the simulation of fluid flows, the lattice gas method, has been generating interest in the automotive community (3). In this approach the partial differential equations of the Navier Stokes equations are not solved directly, instead, models are constructed which obey discrete "cellular automata" rules at the microscopic level, but yield 3-D fluid dynamics at the macroscopic level.

Prediction of the pseudo-noise acting on a panel is only the first step toward prediction of the cabin wind noise. The vibration response of the structure to the wind load and the resulting radiation of noise must be modeled. Wind noise is a broadband phenomenon spanning the entire audible frequency range. At low frequency FEA is an appropriate tool for modeling structural vibration and sound radiation, at high frequency SEA is appropriate. However, the response at mid frequency where the computational requirements are too large for FEA and the modal density is insufficient for the application of SEA presents a challenge. Also, the proper model for the coupling of the complex and spatially nonstationary unsteady pressure fields to structures of finite extent is not well established.

3. Wind Noise CAE Prediction Challenge — semi-empirical modeling. Reliance on unsteady CFD to provide wind loads may not be feasible in the near future. Simple analytical/empirical modeling approaches using scaling law techniques have been utilized to relate steady flow parameters on the driver window to measured interior noise, with some success (4). Coney, Her & Moore (5,6) have extended this approach to consider all of the greenhouse surfaces and more detailed representations of the wind noise loads. Various types of turbulent flows were examined and transfer functions between load and panel vibration were established. They demonstrated experimentally that production vehicle pseudo-noise spectra under some circumstances depend not only on local steady flow conditions but also on conditions upstream. They also showed that significant contributions to wind noise in production automobiles were associated with the roof and other greenhouse surfaces, in addition to the driver window. The challenge aspect of these semi-empirical approaches is the determination of the necessary flow parameters from the limited data which are usually available. In practice, relatively simple models (4) exclude essential physical aspects of the problem, while for more detailed models (5,6), definition of input parameters becomes arbitrary and interpretive.

4. Additional Challenge — flow-structure interaction. In any complete model of automotive wind noise sources, contributions from flow over the various edges and cavities which can be found on an automobile, due to vortex shedding from the antenna, roof racks, etc., as well as that associated with the door and glass edges seal systems must also be considered, lending a significant level of complexity to any realistic modeling effort.

REFERENCES