

Automobile Wind Noise Speed Scaling Characteristics

Hangsheng Hou
China FAW R&D Center

ABSTRACT

Wind noise, an aeroacoustic phenomenon, is an important attribute that influences customer sensation of interior quietness in a moving vehicle. As a vehicle travels faster, occupants' sensation of wind noise becomes increasingly objectionable. The purpose of this work is to investigate the increase of wind noise level perceived by a driver in response to an increase in wind speed. Specifically, it explores how much the level of wind noise at the DOE (driver outboard ear) would vary in response to a change in wind speed based on the test data obtained in a wind tunnel from ten vehicles that belong to several different passenger vehicle segments. The first part of this work studies the change of the SPL (sound pressure level) in response to a change in wind speed U . It shows that the SPL(dBA) approximately scales to $U^{5.7}$ at the DOE and to $U^{6.3}$ in the far-field, which could be interpreted as the dominance of dipoles. The second part of this work looks into the scaling of loudness measured in Zwicker sones that represent the human auditory sensation of wind noise level. It shows that the human perception of the wind noise loudness scales to $U^{1.7}$ approximately, which indicates that the wind noise loudness sensation is doubled when the vehicle speed incurs a 50% increase.

CITATION: Hou, H., "Automobile Wind Noise Speed Scaling Characteristics," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(1):2015, doi:10.4271/2015-01-1531.

INTRODUCTION

The vehicle interior noise level, or otherwise referred to as the interior quietness such as in the J. D. Power APEAL (Automotive Performance, Execution And Layout) survey questionnaire, is an influential attribute that impacts customer satisfaction. Market competition due to increasing customer demand for quieter vehicles has been continuously raising the bar for automobile wind noise design capability as it is a key contributor to the containment of the overall interior noise level. Along with the advancement of technology, there has been considerable progress in recent years on reducing powertrain and road noise, and wind noise is becoming a growing concern as manifested in many third party market research surveys such as the J. D. Power IQS (Initial Quality Study) which carries five items regarding wind noise issues. Manufacturers have been consistently striving for a better understanding and more effective design methodology in pursuit of excellence. Nowadays, wind noise reduction continues to be a major endeavor in vehicle NVH development effort.

The primary source of wind noise is the aeroacoustic noise source generation induced by the turbulent flow in the proximity of the exterior vehicle surface, such as around A-pillar curvatures, body gaps, recesses and protrusions. Typically, as the vehicle speed exceeds 100 kph (kilometers per hour), wind noise could no longer be masked by other noises and stands out as a prominent and objectionable noise source, particularly for low end models that come with minimal sound package contents and insufficient air leakage control. Wind tunnel testing has become an indispensable part of engineering activity during product development processes for all

major OEM's as evidenced by heavy usage of dedicated aeroacoustic wind tunnel facilities. Although significant progress has been made in the wind noise development and simulation area and vehicle wind noise performance keeps improving year over year, a complete understanding of the physics of aeroacoustic noise generation, together with the root-cause based control methods, has still not been accomplished. In an effort to achieve a better understanding of this complex aeroacoustic noise generation phenomenon, many works have been carried out, although mostly in aerospace engineering. The study of speed scaling laws is one of them.

Aeroacoustic noise could be considered as generated by monopole, dipole and quadrupole sources, with the intensity of these sources scaling to wind speeds in terms of different exponents U^4 , U^6 , and U^8 respectively. Wickern and Brenninger [1] carried out the measurements using Audi production cars in the Audi Aeroacoustic Wind Tunnel. By analyzing the obtained data over the frequency spectrum using the reference dynamic pressure scaled with appropriate exponents characterizing U^4 , U^6 , or U^8 dependence, the scaling nature of the sound pressure level may emerge as indicated by the formation of the collapsed curves that correspond to different wind speeds. Their work demonstrated that for a normal production vehicle, the scaling at the DOE (driver outboard ear) as well as in the far-field (3 meters away from the vehicle) is close to U^6 with some deviations, whereas for a fully taped vehicle with blocked underbody flow, U^6 dependence at the DOE holds. Nouzawa et al [2] performed testing in the RTRI (Railway Technical Research Institute) wind tunnel. They found that the measured sound pressure level outside of the vehicle scales with $U^{6.5}$ in the frequency range over 500 Hz. George [3] profoundly illustrated various aeroacoustic sources

around a vehicle. He provided the insights into the noise generation mechanism related to the details of various vehicle surface structures, and also elucidated ways how to analyze and reduce wind noise levels. In [4], he also pointed out that the sound pressure level in the interior and exterior of a vehicle scales close to U^6 .

The generated aeroacoustic noise propagates into a vehicle cabin through various transmission paths such as air leakage openings, sealing imperfections, sound package components and structure panels like glasses especially side glasses and windshields. As a result of this complicated noise propagation process, the wind noise speed scaling at the DOE would be expected to behave differently from the speed scaling outside of the vehicle. In this work, the effort is focused on the wind speed dependency nature of the overall wind noise level at the DOE, i.e. the level perceived by a driver.

Firstly in this work, sound generation theory of aeroacoustics pertaining to the framework of automobile wind noise is briefly summarized. Secondly, the scaling of sound pressure level is investigated, and finally, the scaling of loudness is estimated. The work is carried out based on the wind tunnel measurement results which were collected from several competitive benchmark and vehicle design verification missions during past few months. All test measurements were conducted at SAWTC (Shanghai Automotive Wind Tunnel Center), operational since 2009, maintained and operated by Tongji University located in a northwest suburb of Shanghai. The background noise and repeatability in the wind tunnel are routinely checked so as to maintain data integrity.

There were ten vehicles involved in the test measurements, featuring MPV's, full and mid size sedans, compact, mid, and full size SUV's, and the nameplates included Audi A6 and Q7, Range Rover, Grand Cherokee, Camry, Avanza and other Chinese domestic brands. All test measurements involved in this work were performed under 0° yaw angle condition and with the wind speed sweep following a series of discrete speed values according to a step function with about 1000 milliseconds at a step. No additional modifications of any kind such as taping were involved during all measurements. The measured results were recorded at the DOE with Aachen Heads and processed using ArtemiS.

Those ten vehicles are denoted by the letters A through J queued up in accordance with their wind noise performance ranking from the loudest to the quietest throughout this work. The involved vehicles are equipped with quite distinct wind noise design contents, e.g. some adopt only minimal wind noise containment measures, while others incorporate upscale sound package contents such as comprehensive door sealing configurations, acoustic windshield and side glasses, etc. Vehicles A to C are intended to hit the low end market, and in addition two of them are in fact development prototypes with certain hardware and air leakage issues. C to E are typical vehicles on road with average wind noise performance. G to J belong to the premium segment and are among the market leaders in wind noise perspective.

WIND NOISE SOURCES

Wind noise, i.e. the noise generated aerodynamically by wind due to fast movement of a vehicle, is essentially an aeroacoustic phenomenon. As a proverbial anecdote, the basic equation of aeroacoustics was formulated by Lighthill on the back of a brown envelope during his trip on a train. It was published later titled "Sound Generated Aerodynamically" [5] that became one of his most celebrated works. His masterpiece formed the theoretical foundation of modern aeroacoustics and ushered in an era of aeroacoustics, first flourished in aerospace industry and the like. Lighthill's theory elegantly demonstrated sound generation mechanism by a distribution of quadrupoles, and the power of the noise produced scaling to the eighth power of jet velocity, i.e. U^8 .

Curle [6] considered the influence of solid boundaries upon aerodynamic noise generation and showed that a rigid surface in a turbulent flow may generate sound as well. Curle's considerations led to the conclusion that a rigid object in a turbulent air flow with low Mach number would radiate sound as a dipole. Thus, a sound field can be viewed as generated by a volume distribution of quadrupoles and by a surface distribution of dipoles. Ffowcs Williams and Hawkins [7] extended Curle's theory to include arbitrary convective motion of boundaries, and in this setting, the distributions of sources are essentially monopoles in character involving mass injections or fluxes.

In summary, the aeroacoustic sound field can be expressed as induced by the sum of these three types of sources [8, 9]:

$$p = S_Q + S_D + S_M, \quad (1)$$

where, S_Q , S_D and S_M represent quadrupole, dipole and monopole sources respectively. The formulation of aeroacoustic sources in such simple and succinct emitter forms is also referred to as aeroacoustic analogies, and its application carries with it many details and appropriate assumptions which are beyond the scope of this work and will not be discussed here; only very basic sound source concepts relevant in this work are briefly summarized.

Specifically, for quadrupole sources, S_Q is written as

$$S_Q = \frac{1}{4\pi} \frac{\partial^2}{\partial x_i \partial x_j} \iiint_V \frac{T_{ij}}{r} dV, \quad (2)$$

where T_{ij} is the well-known Lighthill tensor which is of the form $T_{ij} = \rho v_i v_j + p_{ij} - c^2 \rho \delta_{ij}$, with ρ being the air density, v_i the air velocity vector component, p_{ij} the stress between adjacent elements of air, c the speed of sound, δ_{ij} the Kronecker delta, and r is the distance between the source and observer. The double-suffix summation convention is applied.

Equation (2) implies that sound is generated by quadrupoles with strength T_{ij} which is distributed in the entire enclosed region V . In automobile cases, noise sources induced by flow turbulence in the space around a vehicle are quadrupoles. The turbulent flow region is such an example.

The dipole source S_D is of the form:

$$S_D = -\frac{1}{4\pi} \frac{\partial}{\partial x_i} \iint_A \frac{(\rho v_i v_j + p_{ij}) n_j}{r} dA, \quad (3)$$

where (n_1, n_2, n_3) are the direction cosines of the outward normal from A . This equation reveals that sound is generated by dipoles distributed on surface A . There is no net mass flow fluctuations across the boundary, but there is a net momentum or forces across the boundary. The strength of these dipoles is equal to the rate of momentum through A . For automobile applications, if the vehicle is regarded as a foreign body, the first term in the integrand vanishes since air flow velocity in the normal direction of vehicle surface is zero. In this case, a dipole source is basically created by the pressure fluctuations acting on the surface of vehicle.

Finally, the monopole source S_M takes the form:

$$S_M = \frac{1}{4\pi} \frac{\partial}{\partial t} \iint_A \frac{\rho v_i n_i}{r} dA. \quad (4)$$

It is obvious in this case that the sound generation is a result of the rate of variation of local mass flux from A . In automobile situations, such occurrence may be directly linked to vehicle body leakage, as well as aspiration leakage caused by loss of sealing contact created by a dynamically blown-out door due to the pressure load under high speed operating conditions.

It is shown [3,5,6] that the intensity of sound generated by the quadrupoles, dipoles and monopoles scales to the flow velocity differently. For quadrupole sources, the intensity I_Q is related to the wind speed U in the form:

$$I_Q \sim \frac{\rho}{r^2 c^5} l^2 U^8, \quad (5)$$

where l is the characteristic length of the solid structure. The sound intensity I_D associated with dipoles scales to the wind speed U in the order

$$I_D \sim \frac{\rho}{r^2 c^3} l^2 U^6, \quad (6)$$

and for monopoles, the intensity I_M obeys the scaling

$$I_M \sim \frac{\rho}{r^2 c} l^2 U^4. \quad (7)$$

As a natural consequence of these estimates, it is straightforward that

$$\frac{I_D}{I_M} = O(M^2), \text{ and } \frac{I_Q}{I_D} = O(M^2), \quad (8)$$

where M stands for the Mach number $\frac{U}{c}$.

For automotive applications, typical Mach Numbers relevant to normal vehicle usage are around 0.1 which corresponds to the wind speed 122 kph. Therefore, the comparisons in (8) disclose that quadrupole sources are small compared to dipole sources, and likewise dipole sources are insignificant relative to monopole sources. In other words, if there exists a monopole source, it would be a dominant noise source. This is partly one of the reasons that current OEM's prevalent practice mandates tough air leakage target and control by closing body openings and designing robust door and window seals. If monopole sources are under control, then dipole sources would be expected to play a prominent role in automobile aeroacoustic noise generation.

Of course, strictly speaking, discussions on aerodynamic flow topics probably could never be on track without mentioning the classical Reynold's number and Strouhal number, and in fact, rigorously, they should be included in the expressions (5), (6), and (7) as well. For simplicity, such details are not pursued within the scope of this work.

SCALING OF SOUND PRESSURE LEVEL

Sound pressure level, customarily abbreviated as the acronym SPL, is defined as:

$$L = 10 \log \frac{P_{rms}^2}{P_{ref}^2}, \quad (9)$$

where P_{rms} is the root-mean-squared sound pressure given by

$$P_{rms} = \sqrt{\frac{\int_0^{t_0} p^2 dt}{t_0}} \quad (\text{Pascal}), \text{ and } P_{ref} = 2 \times 10^{-5} \quad (\text{Pascal}) \text{ is the reference pressure.}$$

In this work, the goal is not to try to seek a quantitative estimate for the amplitude of pressure fluctuation, but rather to focus on the understanding of how the overall SPL L scales to the wind speed U .

Along the same line as the estimates given by (5), (6) and (7) regarding sound intensity speed scaling characteristics, assume in general that the speed scaling of sound intensity I is $I \propto U^\alpha$ where when $\alpha=4, 6, 8$, the assumption represents the cases corresponding to monopole, dipole, and quadrupole sources respectively. The task here essentially boils down to the estimation of α for the overall SPL.

From sound theory, it is known that the intensity $I \propto P_{rms}^2$. Therefore it follows that

$$P_{rms}^2 \propto U^\alpha, \quad (10)$$

which once combined with (9) leads to

$$L = 10\alpha \log U + D, \quad \text{Documents}$$

Document Sharing Hub