

The Influence of the Acoustic Transfer Functions on the Estimated Interior Noise from an Electric Rear Axle Drive

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ABSTRACT

In the vehicle development process, targets are defined to fulfill customers' expectations on acoustic comfort. The interior complete vehicle acoustic targets can be cascaded down to system and component targets, e.g. insulation properties and source strengths. The acoustic transfer functions (ATFs) from components radiating airborne noise play a central role for the interior sound pressure levels. For hybrid vehicles fitted with an electric traction motor, the contribution of high frequency tonal components radiated from the motor housing needs to be controlled. The interior sound pressure due to an airborne motor order can be estimated by surface velocities and ATFs. This study addresses the ATFs measured from a large number of positions located around an electric rear axle drive (ERAD) and their influence on estimated interior noise. First, the magnitude variation between the individual ATFs and how it clearly can be visualized was presented. Displaying all ATFs in a color map revealed the magnitude at each geometrical location of the respective microphone. Secondly, the influence of the ATF's spatial resolution on estimated interior sound pressure was investigated. This was done for theoretical models of the stator shell source shape and also for measured surface velocities. By reducing the spatial resolution from 0.05 to 0.10 m between each microphone, the difference in noise contribution is typically within three decibels with a 12th octave smoothing filter applied to the narrow-band data. The findings from this work provide insight in the risks of compromising with the number of ATF's needed for contribution analysis.

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1. INTRODUCTION

With the introduction of pure electric and hybrid-electric passenger cars, several new challenges have arisen for noise and vibration engineering. With the absence of the masking noise from the internal combustion engine, more rigorous requirements on components such as electric motors are often needed in order to succeed with the acoustic performance. The electric traction motor is characterized by speed-dependent high-frequency tonal components. Besides the vibro-acoustic properties of the source, the transfer functions relating the source to the receiver are responsible for the interior sound pressure level. Typically, a component target is derived from the complete vehicle sound pressure target and the transfer function(s). However, there are uncertainties about how the transfer functions should be handled, e.g. the amount of transfer functions needed. This study focuses on experimentally determined acoustic transfer functions (ATFs) from an electric rear axle drive (ERAD) and their influence on estimated airborne interior noise.

1.1. Objectives

The main objective of this study was to investigate the influence of the ATF's spatial resolution on the estimated interior noise.

The first question addressed is how the ATFs from many positions around the ERAD surface to a fixed response position vary in magnitude and how the variation can be clearly visualized. With a large amount of data due to many individual ATFs, a standard two-dimensional plot displaying magnitude versus frequency would present the spread in the data but the linkage to the spatial locations would be difficult to visualize. In addition, this paper presents a procedure for how to place the ATFs according to their spatial locations in a position matrix and visualizing their magnitudes in a color map.

The second question concerns the spatial resolution of the microphones used for the ATF measurements; is it necessary to use such a high resolution as 0.05 m between each microphone? A high number of measurement points require a large

number of microphones, a multi-channel acquisition system and is more time-consuming. The most important in the end is to have a reliable prediction of the noise contribution, so the question needs to be evaluated with respect to interior noise. This was done by combining ATFs of different spatial resolutions with the ERAD's stator shell surface velocities. The velocities were both theoretically derived and obtained from measurements.

Finally, a comparison between two different approaches of estimating the interior sound pressure was performed. The approach of using the product of the spatially averaged squared ATF and the spatially averaged squared velocities (proportional to the radiated sound power) was compared with the sound pressure obtained by summation of partial uncorrelated pressures from element-wise multiplication. The hypothesis is that with a rapidly rotating electromagnetic field, the velocity distribution will be almost uniform; hence the two approaches should yield similar results.

Due to the complex geometry of a vehicle and the fact that the electric motor airborne noise is dominant in the high frequency range, typically above 1 kHz, experimental determination of the ATFs is well suited. With short wavelengths in comparison to the geometrical dimensions, variability in the magnitude of the ATFs around the ERAD is expected to be significant. The findings can provide guidelines on the amount of ATFs required for various analyses. Examples of activities when ATFs need to be extracted are transfer path analysis (TPA), definition of source component targets (e.g. radiated sound power) and evaluation of trim items such as carpets or other isolating and absorbing partitions.

1.2. Electric Motor Noise in Vehicles

Numerous authors have highlighted different aspects on the topic of noise phenomena caused by the introduction of electric machines in vehicles. In [1], the relationship between the prominence of tonal components from the electric motor in electric vehicles and annoyance ratings was investigated. New engineering challenges due to the customers' expectations and demands are explained in [2, 3]. In [4, 5, 6], focus is on technical integration of power electronics and means for noise reduction.

The electric traction motor, typically a permanent magnet synchronous motor (PMSM), emits speed-dependent high-frequency tonal components (orders). Each order originates from an electromagnetic force wave in the air-gap between rotor and stator which results in a mechanical excitation of the structure. Each individual order resulting in interior noise needs to be controlled. Figure 1 demonstrates the distribution of surface velocity orders on the ERAD stator shell from a run-up used for the case study in this paper.

Figure 2 illustrates a schematic representation of the factors determining the interior cabin sound pressure levels due to vibrations caused by the electromagnetic forces. Rotating

electromagnetic pressure waves in the air gap between rotor and stator creates tangential and radial forces. The radial components cause a forced surface vibration on the stator shell. The magnitude and deflection shape of the stator shell depends on its mechanical properties. When the coupling between the structural wave and the surrounding air is strong, the radiation efficiency reaches its peak resulting in excessive sound power radiation [7,8]. Finally, the ATFs between stator shell and interior cabin is the last factor that influence the interior sound pressure response.

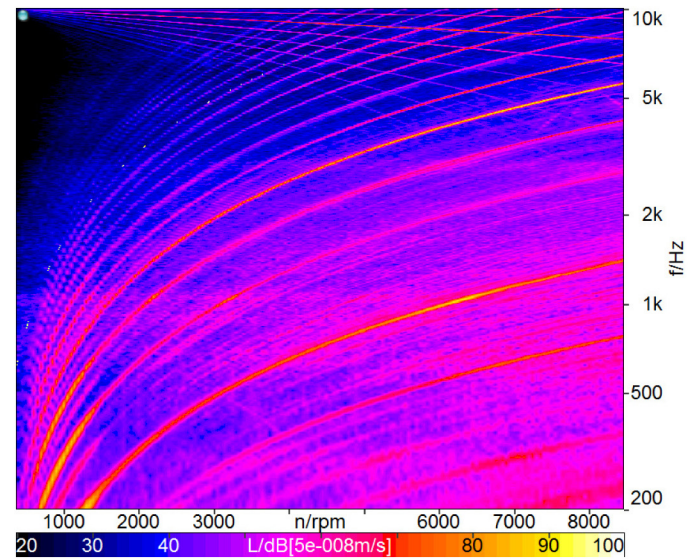


Figure 1. ERAD stator shell average surface velocity during run-up. It illustrates the many harmonics present.

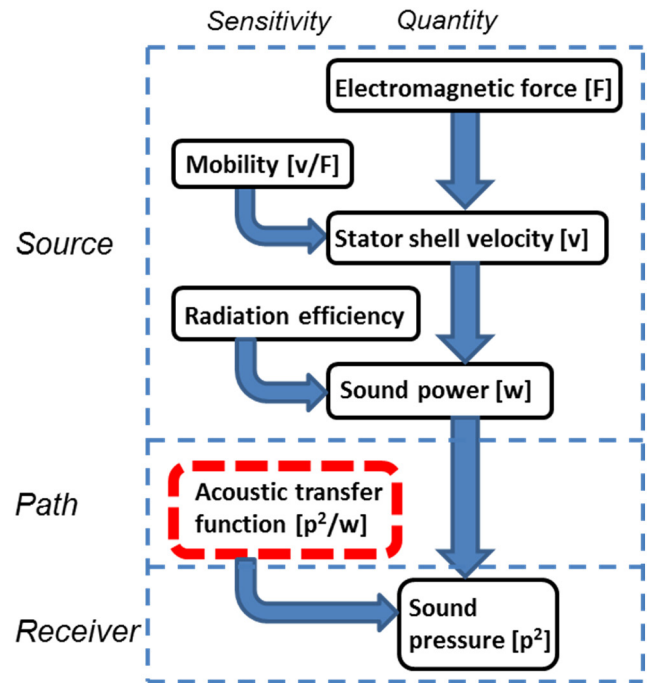


Figure 2. Schematic view over factors that determine the level of the airborne ERAD noise. The acoustic transfer functions will be highlighted in this paper.

2. BACKGROUND THEORY

The most established measure for acoustic noise quantification for electric motors in industrial applications is sound power. The standard ISO 1680:1999 [9] contains a test code for the measurement of airborne noise emitted by electrical machines. Sound power can be determined by means of sound pressure measurements in specific environments (anechoic, hemi anechoic, reverberant chambers) described in the ISO 3740-series [10]. In addition, sound power can be determined from intensity measurements [11] and also velocity measurements for vibrating structures.

The sound power w radiated from a vibrating body is proportional to the squared velocity and is expressed as:

$$w = \sigma \rho_0 c_0 S \langle |v|^2 \rangle \quad (1)$$

Where

σ is the radiation efficiency.

ρ_0 is the density of air.

c_0 is the speed of sound in air.

S is the area of the vibrating body.

$\langle |v|^2 \rangle$ is the spatial average of the rms absolute value of the squared velocity.

Utilizing sound power for the acoustic source characterization, the ATF must relate the interior squared sound pressure to a unit sound power in order to estimate the interior noise.

Since this paper focuses on the relative difference in interior noise for different spatial resolutions of the ATFs, neither the sound power from the ERAD nor the sound power of the substitution source needs to be fully determined. It is enough to note that $w \sim v^2$ and that the ATF $\sim p$. For that reason, the ATF was calculated by the H_1 estimator according to (2) in order to reduce the influence of random noise in the output signal.

$$ATF = H_1 = \frac{S_{xy}}{S_{xx}} \quad (2)$$

Where

S_{xy} is the cross-power of the complex-conjugate of the reference microphone (which is positioned close to the orifice of the source), X^* , and the output sound pressure, Y .

S_{xx} is the auto-power of the reference microphone sound pressure.

For high frequency noise contribution applications within vehicle acoustics, phase information is often neglected and the interior noise is estimated by summation of the uncorrelated pressures [12]. However, since the sound power from a vibrating structure is obtained from the spatially averaged squared velocity, the sound pressure estimation in this paper is derived from averages of squared velocities and ATFs according to (3).

$$p^2 \sim \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m |ATF_{ij}|^2 * \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m |v_{ij}|^2 \quad (3)$$

Where n and m are indexes for surface elements.

With a symmetric vibration pattern, power radiated from the entire surface multiplied by the average ATF will yield the same results as element-wise obtained partial pressures. The partial pressure approach is often used for TPA. A comparison between the average approach and the partial approach is evaluated for measured velocities in the result chapter 3.3.2.3.

As an alternative to sound power, the acoustic loads can be characterized by volume velocity. Volume velocity, or volume acceleration, is commonly used within vehicle acoustics as a source descriptor for engine, exhaust, intake, tires etc. [13, 14, 15]. These descriptors are needed when performing a noise contribution analysis or TPA. Volume velocity is typically determined indirectly through sound pressure measurements. This is done with indicator microphones together with transfer functions relating sound pressure to a unit volume velocity with a calibrated substitution source. These measurements are often only suited when the motor is run in a test rig due to the limited space when installed in a passenger car. It should also be noted that the test rig should be in at least hemi anechoic environment to reduce the influence of reflections. However, obtaining a realistic load on the electric motor can be difficult during test rig operation. For this case study, the ERAD was only available as mounted in the vehicle, hence using sound power, w , to characterize the acoustic loads was preferred.

3. EXPERIMENTS AND RESULTS

3.1. Experimental Setup for Determination of ATFs

Measurements were carried out in a hemi-anechoic chamber. The atmospheric pressure was 1001 hPa, humidity 61% and temperature 22 °C. A station wagon test vehicle equipped with an ERAD was used for the tests. The ISVR HFS high frequency volume velocity source was positioned with the nozzle in the rear seat inside the vehicle. The ISVR source consists of a driver in a cubic box with a rubber hose attached