

Determination of Radiated Sound Power from an Electric Rear Axle Drive In-Situ and its Contribution to Interior Noise

David Lennström

Volvo Car Corporation, NVH Center

Roger Johnsson, Arne Nykänen, and Anders Ågren

Luleå University of Technology

ABSTRACT

System and component target setting for noise and vibration are important activities within automotive product development. New challenges arise when electric motors are introduced into cars traditionally powered by combustion engines. The emitted noise from an electric traction motor for hybrid electric vehicles is characterized by high frequency tonal components from the dominating magnetic harmonics which can be perceived as annoying. Sound power is frequently used for quantifying the airborne noise from rotating electrical machines. This paper describes the process of determining the radiated sound power from an automobile electric rear axle drive *in-situ* and its contribution to interior cabin noise for a prominent rotor order. The sound power was calculated by combining the average stator surface vibration velocity together with an estimate of the radiation efficiency. To model the radiation efficiency, the vibration shape of the cylindrically shaped stator shell was determined by means of operational deflection shapes. The acoustic transfer functions between the source and receiver positions close to a passenger's ear, were defined as the ratio of sound pressure and sound power. By combining the acoustic transfer functions with the calculated operational sound power, the airborne interior noise can be predicted. The calculated interior noise levels were found to be in accordance, within approximately 3 dB, with the measured airborne noise from the stator shell. This indicated that the method is valid and could be helpful for calculating allowed radiated power from interior noise targets and acoustic transfer functions.

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1. INTRODUCTION

In order to succeed with the acoustic performance of passenger cars, requirements need to be defined and fulfilled for noise emitting and transferring components and systems. A modern car consists of numerous such components, e.g. fans, alternator, compressors, pumps and motors for various functionalities. The requirements need to cover both the airborne and structure borne contributions that add up at the receiver position.

The objective of this paper is to present and evaluate a method for setting requirements for the allowed levels of radiated tones from an electric automotive traction motor. The method is limited to a cylindrically symmetrical source structure. If the interior noise can successfully be estimated by the obtained sound power combined with its respective

transfer functions to the interior receiver position, then the allowed radiated noise levels needed to reach the desired interior sound pressure targets can be determined. Lindbom [1] found that the levels of high frequency tonal components from an electric drive should not exceed the masking background noise levels of the respective critical band in order to avoid annoyance. However, details on the requirement setting process itself and the derivation of the interior sound pressure target will be left out in this paper.

1.1. Case Study Definition

The object of the case study was an electric rear axle drive (ERAD), installed to drive the rear wheels in a parallel plug-in hybrid electric C/D class station wagon. Due to high power density, absence of brushes, high torque/inertia ratio and

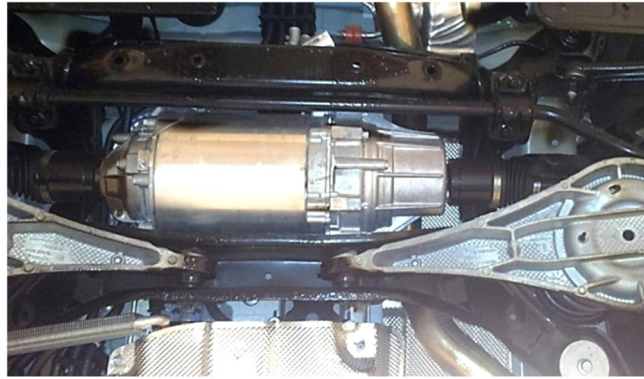


Figure 1.1. The electric rear axle drive (ERAD) including clutch housing, stator shell and gear box.

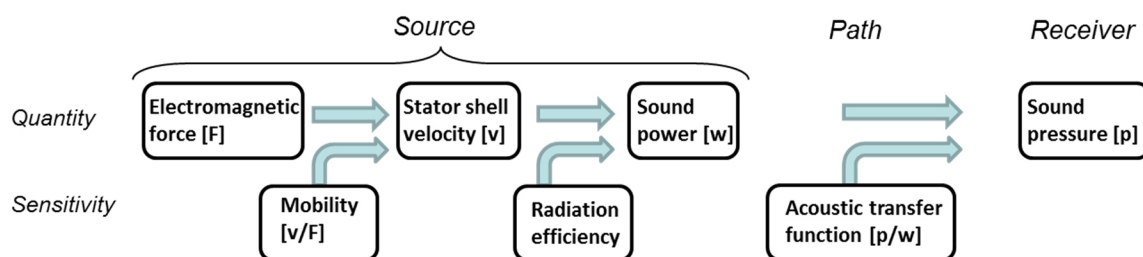


Figure 1.2. Schematic view over factors that determine the interior level of the airborne ERAD noise.

negligible rotor losses [2], the permanent magnet synchronous motor (PMSM) is the most common motor type for automotive applications. The ERAD fitted to the vehicle in this study is a PMSM with cylindrical stator shell. The electric motor stator shell connects to a gear box and clutch housing according to Figure 1.1. There is a fixed gear ratio between the driving wheels and the rotor speed.

The method of determining the sound power *in-situ* by using vibration velocity and radiation efficiency will be presented in this paper. The reason for using this method was the limitation that the ERAD of interest was only accessible when installed in vehicle. While mounted in the vehicle, the free space around it is restricted, which makes it difficult to fit microphones or an intensity probe at all desired locations. A benefit with performing measurements on the ERAD installed in vehicle compared to running it alone in test bench is that the loading of the electric motor is more similar to real driving conditions, which assures correct excitation.

1.2. A “Source - Path - Receiver” Model

Due to electromagnetic radial forces in the air gap between the rotor and the stator, the stator shell will vibrate and radiate speed-dependent tonal components, usually with high frequency contents. Further details on the noise generating mechanisms will be left out in this paper. This study includes the airborne contribution solely which is expected to be dominant for a majority of the tones above 1 kHz.

The two main properties determining the interior noise is the source's acoustic loads and the acoustic transfer function (ATF). The acoustic load was characterized by the radiated sound power and the ATF as the ratio of sound pressure and sound power. Aspects on these two factors will be highlighted more in detail further on. The estimated noise levels for the ERAD were compared to the measured interior noise levels as a way of validating the adequacy of this analysis method.

A source, path and receiver model covering the parameters that influence the radiated ERAD noise and its propagation to the interior cabin response is depicted in Figure 1.2. The radial dynamic forces cause the stator shell to vibrate and radiate noise [3]. If eigenfrequencies of the stator shell interact with the excitation frequencies, the vibrations are amplified. The radiated power from the stator shell at a certain frequency is proportional to the squared surface vibration velocity and the radiation efficiency. Dupont [4] and Roivainen [5] give explanations of the importance of the space-frequency content of the force waves and show examples of how a force wave of low spatial order (e.g. spatial order 0, corresponding to a circumferential uniform excitation) can be present in a wide frequency range. The force waves can rotate in both positive and negative direction in the air gap between stator and rotor. Numerous authors provide descriptions on the ability of structures such as cylinders to radiate sound in air depending on the exciting circumferential wave number order [6, 3, 7]. Finally, the ATF determines the filter between the emitted noise from the

stator shell to a given response position, e.g. in the interior of the car.

1.3. Acoustic Source Characterization

The most established measure for airborne noise quantification for electric motors in industrial applications is sound power. The standard ISO 1680:1999 [8] contains a test code for the measurement of airborne noise emitted by electrical machines. Sound power can also be determined by means of sound pressure measurements in specific environments (anechoic, hemi anechoic, reverberant chambers) described in the ISO 3740-series. In addition, sound power can be determined from intensity measurements [9] and also velocity measurements for vibrating structures.

As an alternative to sound power, the acoustic loads can also be characterized by volume velocity. Volume velocity, or volume acceleration, is commonly used within vehicle acoustics as a source descriptor for engine, exhaust, intake, tire etc. [10, 11, 12]. These descriptors are needed when performing a noise contribution analysis or transfer path analysis (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.

For traditional airborne low to mid frequency TPA, the acoustic source strength is usually defined for a sub area smaller than half a wavelength of the highest frequency of interest. That partial source is then regarded as an equivalent monopole point source with a certain magnitude of volume velocity and phase. There is also a corresponding transfer function between the source and the receiver defined as the ratio of sound pressure and volume velocity. The partial pressure contributions at the target locations in the interior of the vehicle are summed up with respect to phase information. For high frequency applications, the wavelengths are short in comparison to the vibrating structure's dimension and the phase relations between the different partial sources and the receiver position are of more random nature. Trying to model each partial acoustic source as an equivalent monopole with phase information and a respective transfer function would not only be impractical due to the large amount of microphones needed, but also non robust since the magnitude and phase relations can vary between different frequency components. Verheij [13] proposed a method of treating the partial sources as an average of a set of uncorrelated monopoles. Plunt [14] proposed transfer functions with a certain bandwidth in order to reduce the influence of random variations. The average or sum of different frequency components is yielding a more robust description of the vehicle's filter functions. Working with average functions to a certain extent in both the spatial and the frequency domain has been established as good practice for high frequency acoustic applications. Typically, the acoustic filter between the exterior and interior of a trimmed car body has small local differences in magnitudes which make working with

frequency bands appropriate. The major high frequency noise phenomena in vehicles are also often to some degree broad band in its character, e.g. combustion noise, tire noise, wind noise etc. In these cases, using frequency band averages is suitable for describing the source, path and receiver. However, for an electric motor with a very tonal character, using broad band data to describe the source characteristics might not be sufficient. In this study, narrow band frequency intervals have been used for the source and the receiver while the transfer path characteristics have been described with smoothed narrow band data.

There are a few simplification steps involved in the calculations, e.g. in the estimation of the radiation efficiency and the fact that the average ATF and sound power levels are used. The ATF used as a descriptor of the vehicle's filter function between the stator shell and the interior receiver microphones was defined as the ratio of sound pressure and sound power. Due to the facts that the stator shell has a cylindrical body and the electromagnetic excitation is symmetric along the circumference, the sound radiation directivity is expected to be cylindrically symmetric. With a symmetric directivity, the average approach used in this study should be feasible.

2. SOUND POWER FROM THE STATOR SHELL

2.1. Background Theory

The radiated sound power and noise contribution was in this study determined for the single most prominent airborne harmonic of the rotor speed for an acceleration 0-100 km/h on a rolling road dynamometer. The radiated sound power is proportional to the average squared velocity over the vibrating area according to (2.1) [7]:

$$w = \sigma \rho_0 c_0 S \left\langle |v|^2 \right\rangle \quad (2.1)$$

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.

$\left\langle |v|^2 \right\rangle$ is the spatially averaged squared rms absolute value of the surface velocity.

The radiation efficiency, σ is defined as the ratio of the acoustic power radiated and the acoustic power radiated of a piston with the same velocity [15]. There are several theoretical models for the radiation efficiency of a cylinder