

Study on the Vehicle Cabin Noise Employing the Interfacial Friction in Double Layered Frames Used in Electric Vehicle Traction Motors

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ABSTRACT

Electric vehicles are considered not only eco-friendly but also quieter than vehicles with conventional internal combustion engines. However, less noisy environments in cabins make passengers feel uncomfortable to moderate noise. This paper discusses noise reduction for electric vehicles radiated from traction motors. In the analysis of the noise generation mechanisms it is demonstrated that frequency ranges of the highest level in the noise spectrum of electromagnetic harmonic orders of the induction motor coincide with structural resonances of the motor housing. Interfacial friction between the inner and outer housings of the motor is employed in reducing structural vibration of the motor. Measured noise in the cabin and vibration at the motor housing indicates that slip damping presented from interfacial friction between the inner and outer housing is effective in reducing noise from the traction motor and in the cabin.

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INTRODUCTION

Global warming issues with CO₂ emission by cars and rapidly diminishing fossil fuel have forced car manufacturers to develop more environmentally friendly and fossil fuel free cars. In order to meet this demand, there has been comprehensive research on electric cars mainly in that electric vehicles have zero CO₂ emission and can enhance energy efficiency using regenerative braking in which they recover kinetic energy and charge battery during deceleration and stop [1, 2]. In the view of NVH, electric vehicles are known as more silent than conventional vehicles because they remove combustion engines which are the main source of the noise and vibration of vehicles. However, in practical development processes noise issues in electric vehicles are more complicated. Quieter environments in a passenger cabin using electric motors for traction of the car instead of combustion engines make unwanted noises become more prominent. This paper presents experimental research on electric vehicle cabin noise reduction. Particular concerns are on structural integrity of the traction motor. Many researchers reported that structural vibration of the stator core dominates

the noise and vibration of the motor system [3, 5]. However, in this research it was shown that structural characteristics of the assembled system of stator core and frame contribute to noise radiated from the traction motor. From the experimental modal analysis results of the traction motor contributions of the structural resonances on the vehicle cabin noise was illustrated.

Interfacial damping of the traction motor frame was employed in order to reduce the resonant vibration and noise emission from the traction motor. Researchers like Banks and Nada, [6, 9] reported that significant damping can be obtained in the frictional interfaces with fastening pressure to allow some interfacial slip on a simplified geometry such like double-layered beam, sliding joints. This paper presents a practical application of interfacial damping to an electric vehicle NVH problem. 100 kW Fuel Cell Electric Vehicle (FCEV) traction motors and 60 kW Electric Vehicle (EV) traction motors were used for the noise measurement and modal tests.

INTERFACIAL CONTACT SURFACE AND FRICTIONAL DAMPING

The physical mechanisms of damping, whatever the specific sources of it is such as external friction, fluid viscosity and internal material friction, have been studied extensively and are still complicated physical phenomena. However, energy dissipation can be demonstrated with a typical physical phenomenon already well understood. Coulomb damping, for example, is used to represent dry friction present in sliding surfaces. For this kind of damping, the force resisting the motion is assumed to be proportional to the normal force between the sliding surfaces. The governing equation of motion and the energy dissipation, damping forces, for a simplified 1-dimensional mass -spring system is as follows,

$$m\ddot{x} = -\text{sgn}(\dot{x})f_f - f_k - f_c \quad (1)$$

Where f_f is the friction force, f_k is the spring force, f_c is the viscous damping force and $\text{sgn}(\cdot)$ is the signum function depending on the motion of direction. In [Equation \(1\)](#) direction of the friction force is always negative to the direction of the motion regardless of its direction.

In [Figure 1](#) the structure in the middle, double layered beam, with interfacial fastening pressure suffer from resisting force a long with the line of interface when it is under vertical bending vibration motion.

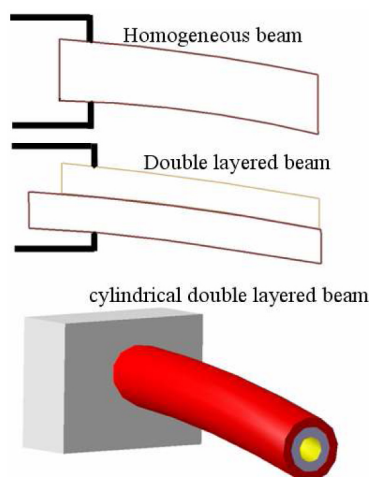


Figure 1. Geometries of beam structures: (a) Homogeneous beam, (b) Double layered beam, (c) Cylindrical double layered beam

When the fastening pressure is enough the strength or rigidity of the double layered beam can be assumed as the same with the homogeneous beam in the top of [Figure 1](#). If the homogeneous beam takes the profile of black solid curve in [Figure 2](#), then double layered beam takes the blue dotted line in [Figure 2](#) due to the interfacial friction or slip damping.

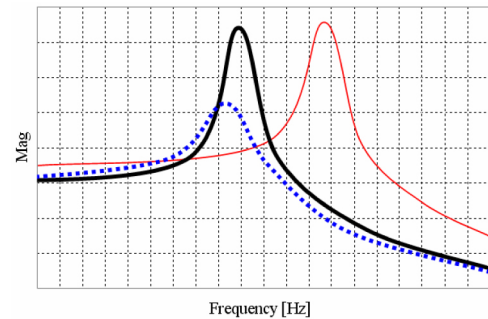


Figure 2. Resonance characteristics of beam structures

For some NVH problems, strengthening the stiffness of the systems is tried. However, increasing stiffness without considering damping mechanism makes the resonance of the system shifted into higher frequency region represented as the thin red line shown in [Figure 2](#). This is why only increasing the strength of the system is not effective in dealing with NVH problems. As stated here, the basic principles of friction damping or sliding damping between the interfacial contact surfaces are just the same with the [Equation \(1\)](#). In general slip normal pressure is governed by the motion of the structure. For this reason slip damping shows effective damping in resonance region as shown in [Figure 2](#). In [Equation \(1\)](#), viscous damping forces are proportional to the velocity of motion and don't exhibit increased damping.

A cylindrical double-layered beam structure is presented in [Figure 1\(c\)](#). This system has a fastening pressure between the inner system and the outer system when the outer diameter of the inner cylinder is larger than the inner diameter of the outer cylinder, which is called an interference fit. It is just the extension of dimension, and the damping mechanism of the system is just the same with dry friction damping and double layered beam case. Later in this paper it will be shown that many electric motors have this type of layouts for the frame and can adopt the proposed methods for the enhancement of NVH quality.

NOISE CHARACTERISTICS OF ELECTRIC VEHICLES AND ELECTRIC MOTORS

Quietness is one of the advantages of electric vehicles along with energy efficiency and zero CO₂ emission. The word, VSP (vehicle sound for pedestrians) supports the quietness of electric vehicles. VSP system is intended to provide auditory cues for pedestrians to help compensate for the quiet condition of electric vehicles and hybrid electric vehicles. It has appeared with the advent of hybrid vehicles and electric vehicles. Conclusively, noise characteristics of the electric vehicle are too quiet. This quietness of the electric vehicle makes it difficult to deal with noise problems such as road noise, wind noise, and reduction gear wine noise etc. However, there has little research on the effect of electromagnetic noise of the traction motor which replaces

the conventional combustion engines on passenger annoyance.

Noise Characteristics of Electric Vehicle

Figure 3 shows the waterfall display of fuel cell electric vehicle cabin noise. It is measured on a WOT (Wide Open Throttle) driving test, speed range 0 to 12,500 rpm, with the traction motor speed rpm referred. Some of the high noise level instances are highlighted in circles in Figure 3. The most disturbing instances in the tracking noise are pointed out to around 3,000 rpm and 8,000 rpm. Noise around 3,000 rpm, area A is related with reduction gear of which reduction ratio is 7.95. The highlighted noise in the circle A is the 2nd harmonics of reduction gear components. And, the most uncomfortable noise in the subjective listening test, the objective of this research, was designated to high frequency pure tones around 8,000 rpm. Even though sound pressure level is comparatively low and time duration is short, subjects in the tests appointed area B to be reduced or improved. As reported in many research [10, 11, 12], annoyance of the noise was not directly related with the absolute sound pressure level but depends on many effects such as its frequency and fluctuation time etc.

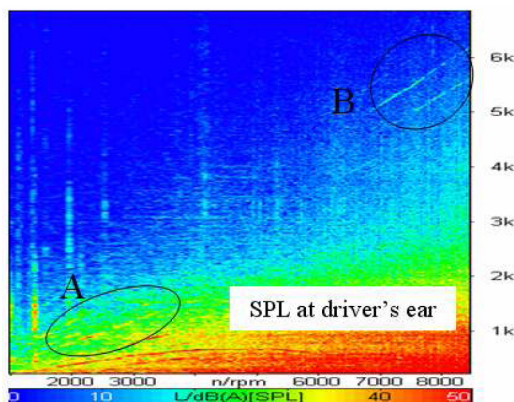


Figure 3. Auto spectrum of Fuel Cell Electric Vehicle cabin noise on a WOT driving test (traction motor speed rpm referred).

In order to reduce the noise in the area B, first of all, what parts of the vehicle generate that component noise is to be identified. Continuously long stretched line traces in waterfall diagram in Figure 3 indicate that the concerning noise components are the harmonic orders of the fundamental rotation. Order analysis of the tracking noise presents its order as follows,

$$\text{Harmonic Order} = \frac{\text{Frequency}}{\text{rpm} / 60} \quad (2)$$

For the noise components in circle B concerning frequency is 5,300 Hz, and the rotational speeds are around 7,400 rpm and 8,000 rpm. Thus, the noises concerned are 40th

and 44th orders. Later in this paper, it will be explained that these harmonic orders are generated by the electromagnetic forces of the traction motor and typical excitation characteristics of induction motors regarding their slot combinations.

Figure 4 represents the order cut noise spectrums representing 15.9th order and 44th order trace. Both of them are related with transmission of the vehicle. The first one is attributed to reduction gears. There have been many papers in the issues called transmission error of the reduction gear [13, 17]. The concerning issues of this research is focused on the 40th and 44th orders. Albeit the sound pressure level of the 15.9th order is higher than that of 40th and 44th orders around 7,500 rpm, annoyance due to 44th order noise peak is much higher. Annoyance of the passengers didn't depend on the absolute level of noise but on various factors. For the concerning case abrupt increase in sound pressure level and the quietness of neighboring frequency regions contribute to the annoyance despite its low sound pressure level.

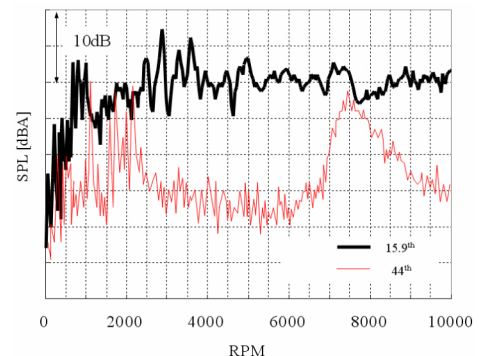


Figure 4. Order cut noise spectrum for 15.9th order and 44th order (traction motor speed rpm referred)

NOISE GENERATION OF THE INDUCTION MOTORS

Figure 5 shows section view of the traction motor electric parts. For induction motors, electromagnetic harmonic orders of stator slot and rotor slot and their combinations generate severe pure tone excitations. Among them typical electromagnetic excitations related with rotor slot and stator slot are given as follows,

$$\begin{aligned} EMF_S &= N_{SS} \pm P \\ EMF_R &= N_{RS} \pm P \end{aligned} \quad (3)$$

Where EMF_S is excitation orders due to the stator slot, EMF_R is excitation orders due to rotor slot, N_{SS} and N_{RS} are the number of stator slot and rotor slot, respectively, and P is the number of pole.