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Abnormal Electromagnetic Noise of Motors depending on Fixing Methods of Permanent Magnets

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Abstract

Abnormal electromagnetic noise of traction motor in hybrid electric vehicle (HEV) occurred after the endurance test is experimentally investigated. Theoretical model explains that the abnormal components, which are ±1 orders of the number of slots, can be sourced from an unbalanced rotor. Experimental approach confirms that the abnormal noise is mainly from the rotor. Since there are no variations in the strength of the magnet flux, the vibration of the magnets is strongly believed as the main reason of the abnormal noise. Finally, the magnetic fixing method is changed from bond to mold, and the improvement of the noise is demonstrated.

Keywords: abnormal electromagnetic noise, hybrid electric vehicle, permanent magnet, unbalanced force, vibration

1 Introduction

Noise, vibration and harshness (NVH) of powertrain system in Hybrid Electric Vehicle (HEV) have brought new issues due to the particular characteristics of the motor noise [1]. Even though the level of motor noise is relatively low, the powertrain noise without engine firing can be easily perceptible to customers since masking effect from the internal combustion engine (ICE) is weakened. Indeed, the frequency range of interest may be high such as around 1 kHz (it can vary depending on the number of pole/slot combination), and it is a sensitive range for human ears. Nonetheless most issues for the motor whine noise from the electromagnetic force such as cogging torque and torque ripple have been suppressed by optimizing topologies of motor through computational analysis [2-11]. The abnormal electromagnetic noise, however, may be more annoyed due to the uncorrelated characteristics to the motor RPM, and it can come from multiple sources such as defects in bearing, electromagnetic design, winding pattern, or imperfection magnetization.

A few reasons for the abnormal electromagnetic noise have been widely studied by numerous researchers. Yoon (2005) [12] shows that unbalance magnetic forces have greater effects on motor noise than cogging torque does. Jang et al. (1996) [13] demonstrated how unbalanced magnetic forces may be determined by pole-teeth-winding configuration using FEM. Arata et al. (2011) [14] investigated asynchronous rotation-frequency noise and vibration of permanent magnetic motor. They assumed that the eccentricity caused by clearance at stator bolting points would be source of the noise. Finley et al. (2000) [15] explained various source of vibration problem in induction motors. In their diagnostic chart, unbalanced motor could create change in the 1st order component of rotating speed in motor vibration. Hartman and Lorimer (2001) [16] investigated motor vibration due to defects in motor and explained that most common defect in practice is from imperfect magnetization. Im et al. (2012) [17] studied, theoretically, a sensitivity based on change of design parameters to BLDC motor performance. They considered the effect of the eccentricity for the parameters, but did not further investigate what could cause the eccentricity. Lee and Jang (2008) [18] explained that an unbalanced magnetic force can lead vibrations for the first harmonic and the ±1 harmonics of slot number. Also, they demonstrated that the unbalanced magnetic force can be caused by uneven magnetization of the permanent magnet, rotor eccentricity, and stator eccentricity.

In practice, the abnormal electromagnetic noise is often observed in the manufacturing level and becomes serious problem, and previous dedicated investigations reveal that the abnormal noise can come from various sources. However, there is no paper, as far as authors know, reporting an abnormal noise due to fixing methods. This paper introduces the investigation of the abnormal electromagnetic noise in motor and the improvements. Potential abnormal noise sources including mechanical and electromagnetic unbalanced forces are examined experimentally. Reduction of the abnormal noise by changing the fixing method for magnets in rotor is demonstrated in HEV test.

2 Magnetic Unbalance of HEV Traction motor

2.1 Mechanical and Electromagnetic Factor

Figure 1 illustrates the HEV traction motor which consists of the rotor, stator and cover as design parameters are shown in Table 1. Fundamental sources of electromagnetic noise of the HEV traction motor are the cogging and the torque ripples. The fundamental harmonic order of the cogging torque ripple is decided by the least common multiple of the number of pole and slot, and that of the torque ripple is 6 times of the number of the pole pair. HEV motor used in this paper has identical harmonic order of 48^{th} for

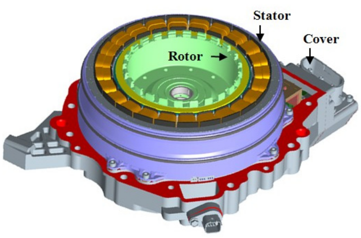

Figure 1 HEV traction motor

Table 1 Specification of HEV traction motor

Classification	Content
Motor Type	IPMSM
Number of Pole/Slot	16 / 24

cogging torque and the torque ripple because this motor has 16 poles and 24 slots.

In development process, the motor has to be qualified for endurance tests. One of the main concerns of the endurance tests is that NVH performance should be sustained after the tests. Figure 2 shows comparison of colour-map of noise, which is measured in cabin room, of the HEV traction motor in driving test (while breaking the vehicle from 40 to 5 kilometer per hour). “Initial condition” represents that the motor tested is just manufactured, and “endurance test” means that the motor has been through the endurance tests. Initial condition test shows mainly the 48^{th} order component, which is the main order component of the motor, and a weak second harmonic. However, endurance tested motor has brought new components of 23^{th} and 25^{th} order around 0.4 – 0.6 kHz frequency range. Those components may create uncomfortable cabin noise and could be worse as time goes; as a result, the endurance test is failed.

The primary cause of mechanical factor of magnetic unbalance can be classified by the eccentricity of stator and rotor. The eccentricity of stator and rotor destructs the uniform air gap between stator and rotor and bring the magnetic unbalance of the electromagnetic structure of HEV traction motor. The primary cause of electromagnetic factor for the magnetic unbalance can be classified by the asymmetric pole-slot combination and manufacturing errors, such as uneven magnetization of the permanent magnet

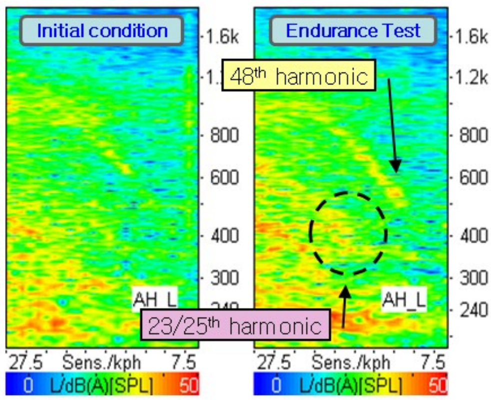

Figure 2 Comparison of cabin noise of HEV between “initial” and “endurance” motors

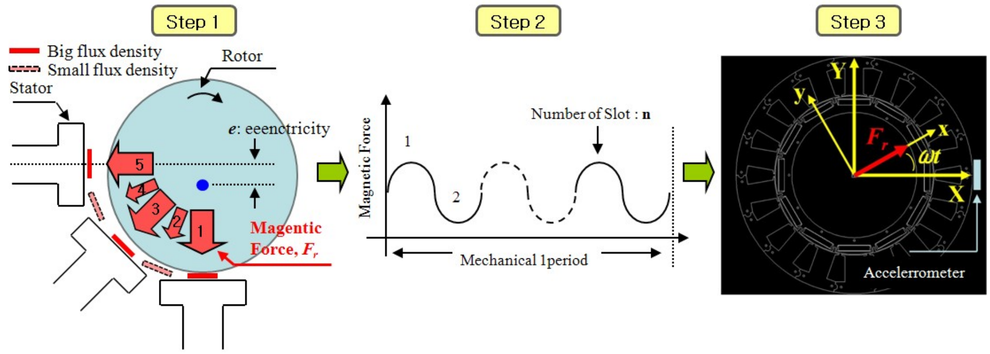

Figure 3 Transfer mechanism of the abnormal magnetic force due to magnetic unbalance

and the position tolerance between the rotor and the permanent magnet.

2.2 Harmonic Order of Abnormal Electromagnetic Noise

Figure 3 shows the transfer mechanism of the abnormal magnetic force of the HEV traction motor due to magnetic unbalance. The magnetic force of the HEV traction motor due to magnetic unbalance is the radial and rotational force. It is proportional to the variation of magnetic flux density of the air gap. Therefore, its magnitude and period is alternated between the stator slot and opening between two slots and affected by the number of stator slot. The rotational magnetic force, F_r is expressed with a Fourier series as follows [18]:

$$F_r = \sum_{i=0}^{n} F_i \sin(il\omega t + \varphi i) \qquad (1)$$

where i, l and ω are the integer, the number of stator slot and the rotational speed, respectively. The rotational magnetic force rotates around the air gap in the rotating coordinate frame, for example, xy, as shown in Figure 3. It may also excite the stator of HEV traction motor for the vibration perspective. Therefore the excited vibration, which can be called abnormal magnetic force, of the rotational magnetic force can be transformed to a fixed stationary coordinate frame, XY, as follows:

$$\begin{aligned} F_X &= \cos(\omega t + \phi)\sum_{i=0}^{n} F_i \sin(il\omega t + \varphi_i) \\ &= \frac{1}{2}\sum_{i=0}^{n} F_i[\sin\{(il-1)\omega t + \varphi_i - \phi\} \\ &\quad + \sin\{(il+1)\omega t + \varphi_i + \phi\}] \\ F_Y &= \sin(\omega t + \phi)\sum_{i=0}^{n} F_i \sin(il\omega t + \varphi_i) \\ &= \frac{1}{2}\sum_{i=0}^{n} F_i[\cos\{(il-1)\omega t + \varphi_i - \phi\} \\ &\quad - \cos\{(il+1)\omega t + \varphi_i + \phi\}] \end{aligned} \qquad (2)$$

where δ is the phase angle of F_r with respect to the rotating x-axis. The above equations show that the slot effect il is transformed to the first harmonic (i = 0) and the harmonics of slot number ±1 (i = 1,2,3,…). In this paper, the abnormal magnetic force of the HEV traction motor is equal to 23th and 25th harmonic order of the rotating frequency, because the motor have 24 slots.

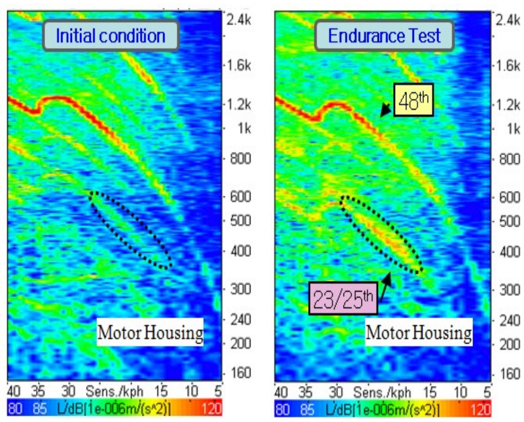

Figure 4 Comparison of traction motor vibration between before and after endurance test

3 Identification and Reduction of abnormal electromagnetic noise

3.1 Experimental Identification

Figure 4 shows a comparison of vibration levels measured at the surface of the motor housing between before and after endurance test. In initial condition, there is only the 48th harmonic order, which is traditional electromagnetic vibration of HEV traction motor due to the cogging torque and torque ripple. However, another 23th and 25th

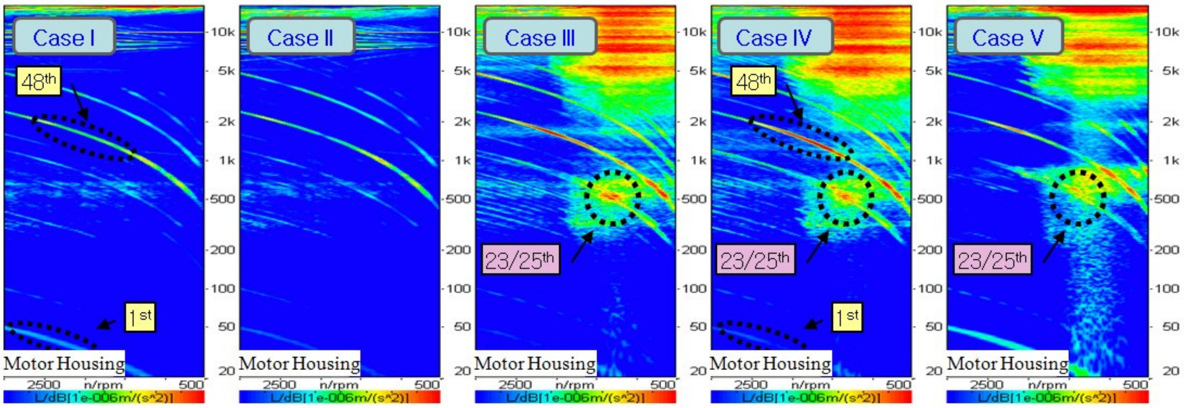

Figure 5 Cross-check between the motors in a state of the initial condition and the endurance test

Table 2 cross-check between the motors in a stator of the initial condition and the endurance test

Item	Case I	Case II	Case III	Case IV	Case V
Stator	Initial	After test	Initial	After test	Initial
Rotor	Initial	Initial	After test	After test	After test
Bearing	Initial	Initial	After test	After test	Initial
Abnormal noise	X	X	O	O	O

harmonic order has been appeared after the endurance test. As mentioned previously, the 23th and 25th harmonic order of the HEV traction motor is the abnormal electromagnetic vibration due to magnetic unbalance. Those harmonic orders are undesirable noise in cabin room, because they annoy human ears easily due to their irregularity. In addition, the level of 48th order also has been increased.

This paper identifies the cause of the abnormal electromagnetic noise due to magnetic unbalance by reverse engineering. Table 2 and Figure 5 show the result of cross-check between the motors in a state of the initial condition and the endurance test. They show that the abnormal electromagnetic noise is affected by rotor of the HEV traction motor. As shown in figure 5, the 1st harmonic order of case I is bigger than that of case III. And the 23th and 25th harmonic order of case V still exists in spite of initial bearing. It shows that the mechanical factor of magnetic unbalance, such as the mass unbalance, the eccentricity of the rotor, bearing are not the cause of abnormal electromagnetic noise. And the 48th harmonic order of case III, IV and V as well as 23th and 25th harmonic order is bigger than that of other cases. It shows that the abnormal magnetic

Table 3 Back EMF of HEV traction motor

Item		Measurement	Result
Back EMF	U-V	57.42 V_{rms}	OK
	V-W	57.43 V_{rms}	OK
	W-U	57.42 V_{rms}	OK

noise is affected by the electromagnetic factor of magnetic unbalance and main cause is inferred from mechanical or electromagnetical manufacturing errors, because the HEV traction motor has a symmetric polo-slot combination of 16 poles and 24 slots.

Table 3 shows the back Electric Magnetic Force (EMF) of the HEV traction motor after the endurance test. All component of the back EMF are satisfied to the design specification so the surface flux density is uniform at all position. It shows that there is no uneven magnetization of the permanent magnet. Finally, the position tolerance between the rotor and the permanent magnet is only cause of magnetic unbalance to affect the abnormal electromagnetic noise of HEV traction motor.

3.2 Reduction of Abnormal Electromagnetic Noise

Figure 6 shows the position tolerance between the rotor and the permanent magnet of HEV traction

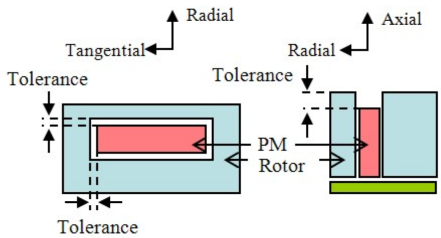

Figure 6 Position tolerances between the rotor and the permanent magnet

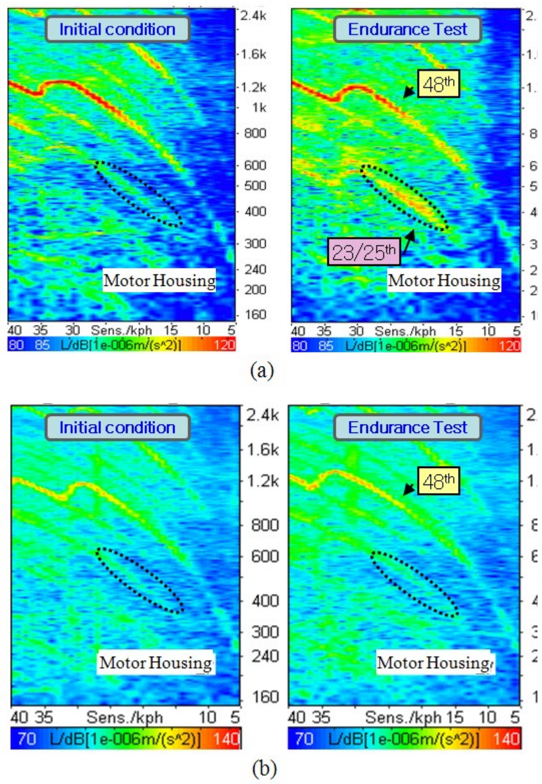

Figure 7 Colour-map of vibration of the original and improved HEV traction motor between before and after endurance test
(a) Original motor (b) improved motor

Table 4 Vibration of the original and improved HEV traction motor between before and after endurance test

Item	Test	Noise	Vibration	
Original	Initial	Good	125 dB	100 dB
	After test	Bad	129 dB	119 dB
Improved	Initial	Good	130 dB	100 dB
	After test	Bad	131 dB	100 dB

motor. This research estimates that the permanent magnet can be vibrated inside the tolerance so the abnormal electromagnetic noise of HEV traction motor has occurred after the endurance test. Therefore, this research minimizes the position tolerance and increase the adhesive strength between the rotor and the permanent magnet. Table 4 and figure 7 show the colour-map of vibration of the original and improved HEV traction motor between before and after endurance test. The improved HEV traction motor has only 48th harmonic order vibration after the endurance test. The vibration level of 23th and 25th harmonic order is equal in a state of the initial condition and the endurance test.

4 Conclusion

This paper investigates the abnormal electromagnetic noise of the HEV traction motor due to vibration of permanent magnet. In the paper, we introduce the mechanical and electromagnetic factor of magnetic unbalance of the HEV traction motor and analyze the harmonic order of abnormal electromagnetic noise due to magnetic unbalance. We determine the characteristics of the abnormal electromagnetic noise experimentally caused by the vibration of permanent magnet. Also, we improve the magnet fixing method of HEV traction motor and reduce the abnormal electromagnetic noise of HEV traction motor experimentally. The proposed method may contribute to improvements of acoustic noise of HEV traction motor for a quite environment in cabin room of HEV.

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