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Design and analysis method for reducing motor NVH and electric vehicle noise validation

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Summary

This paper proposes electromagnetic design and analysis method for noise, vibration and harshness (NVH) of a motor. For an e-Van, named CPEV, exhibited obvious whining noise during driving. To resolve this issue, we analyse the motor force generation from aspects of motor torque and magnetic force. By measuring the interior noise of an electric vehicle (EV), we identify the noise is caused by electromagnetic force. New design motor was manufactured per motor design requirements accordingly. Further validation test for a CPEV equipped with the new motor showed the interior noise level was reduced, especially a 15.3 dB noise reduction at a speed of 20 km/h.

Keywords: IPMSM, NVH, magnetic force, slot pole ratio.

1 Introduction

Interior permanent magnet synchronous motor (IPMSM) is suitable for electric vehicle because it has high torque, wide operation speed and high efficiency. There are demanding requirements for human in EV power system, so it's important to reduce noise and vibration of IPMSMs. For an EV traction motor, it's hard to well-design a motor both in performance and NVH. Even though we have known the noise and vibration are mainly caused by the electric-magnetic forces, cogging torque and torque ripple [1]. Many references show methods to reduce cogging torque and torque ripple. These methods are related to design of stator and rotor shape. Generally, the collocation of slots and poles which called slot/pole ratio is the first step in motor design process, and it's also one of the most decisive factors about cogging torque and electromagnetic force [2].

Slot/pole ratio could decide coil which is concentrate winding or distribution winding. N_{sm} which is the number of slots per magnet pole may find coil pitch [3]. N_{sm} is shown as

$$N_{sm} = \frac{N_s}{N_m} \tag{1}$$

In function (1), N_s is number of slots and N_m is number of poles. Coil pitch is shown as

$$S^* = max\left(fix\left(\frac{N_s}{N_m}\right), 1\right) \tag{2}$$

If coil pitch is equal to 1, PMSM is concentrate winding. On the other hand, PMSM is distribution winding. In normal, concentrate winding have large cogging torque but short end winding. LCM is a simple parameter to choose low cogging torque design. If LCM of slots and poles number is big, cogging torque of PMSM is small [4]. It seems low cogging torque can reduce NVH, but there are still current wave and electromagnetic force may excite

NVH. The relationship between motor frequency and the frequency of cogging torque, torque ripple and normal local force can be resolved [1].

This research presents a method by choosing slot/pole number and stator teeth shape design to reduce NVH in electric vehicles. A real case study is to improve NVH behavior of traction motors. After prototype finished, platform test and vehicle validation test prove that the NVH concern was resolved.

2 NVH measurement results for EV with Gen1 motor

CPEV is a kind of commercial electric vehicle which is developed by ITRI. ITRI designed and validated Gen1 motor and drive system in CPEV. After Gen1 power system and CPEV real vehicle test, we found that CPEV had an acoustic concern of interior sound quality which is audible motor noise. Preliminary validation results was shown in Fig. 1. There were two prominent noise peaks—72 and 73 dB at vehicle speeds of 20 and 50 km/h, respectively. Fig. 2 is the Campbell diagram of CPEV. Interior noise was dominated at 16th and 40th orders of motor speed which are the NVH issue investigated in this research. In addition, the motor studied had a vibration resonance at 1 kHz.

For solving this problem, we checked probably sources which causes the resonance[4]. First we confirmed the cogging torque. Slot/pole number of Gen1 motor is 42/8 for low cogging torque. LCM of slot and pole numbers is related to cogging torque frequency[5], f_{cog}, shown as

$$f_{cog} = LCM \times n \times \frac{f_e}{P} \text{ , n=1, 2, 3...} \quad (3)$$

If n is equal to 1, f_{cog} is 168 orders of motor speed. This order is larger than resonance orders, so we can know that cogging torque is not resonance source. Next we check the electromagnetic force from motor. Electromagnetic analysis software was used to compute rotor force and electromagnetic exciting force on stator teeth.

Electromagnetic force analysis can be calculated by FEM software[6]. Edge force is calculated by 2D FEM analysis model, and surface force at tangent and normal direction is calculated. The force frequency at 3000 rpm is 400*n Hz, n=1, 2, 3, etc. It means the order of mechanical frequency is 8*n order, n=1, 2, 3, etc. If n are 2 and 5, the order will be 16 and 40. As the motor resonated at 20 and 50 km/h, their corresponding motor speeds are 1500 and 3800 rpm. Gen1 motor is 42 slots/8 poles interior permanent magnet synchronous motor, IPMSM, so motor electric frequency values are 100 Hz(mechanical frequency is 25 Hz) and 253.3 Hz(mechanical frequency is 63.3 Hz). For mechanical frequency 1000Hz, value 1 is 1000/25=40 order and value 2 is 1000/63.3=15.8 order that is almost 16 order. These orders are same as motor teeth edge force frequency orders. The vibration mode order was found as order 2 on Gen1 motor.

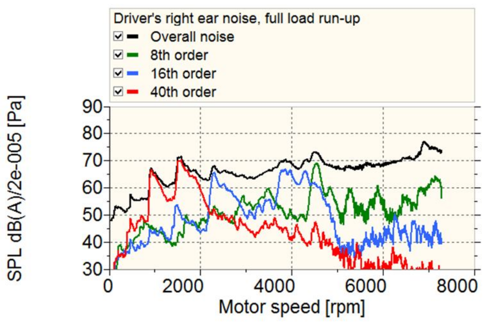


Figure1: Interior noise of CPEV under full load run-up

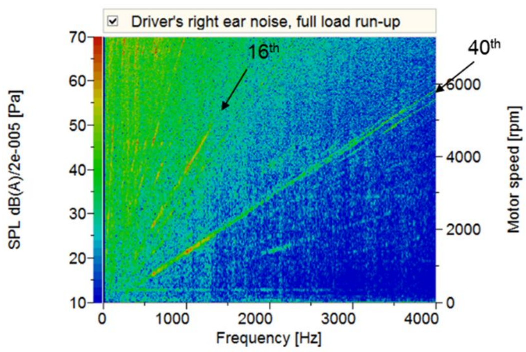


Figure2: Campbell diagram of CPEV under full load run-up

Finally we know the problem is caused by electric-magnetic force, and electric-magnetic force may be designed by ratio of slot and pole number.

3 Motor design and analysis

3.1 Motor slot/pole design for NVH

The effect of pole and slot combination on the vibration and noise in permanent magnet synchronous motor is related by a mode number [3]. The mode number is defined by symmetry number of electromagnetic force. The radar plots of forces shows the vibration mode for slot/pole which are 42/8, 48/8, 54/8, 60/8 (Fig. 3). It also shows the LCM of these designs that is related about cogging torque performance [4].

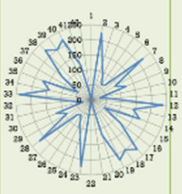
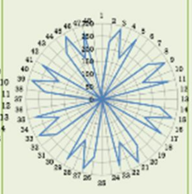
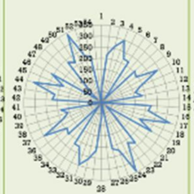
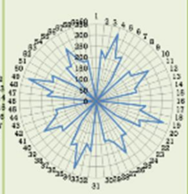
Slot/pole	42/8	48/8	54/8	60/8
Radar plots				
Mode	2	8	2	4
LCM	168	48	216	120

Figure3: Vibration mode for different slot/pole ratio

When mode number are 2 and 3, the displacement of the stator core is big. Therefore, if we want the motor design have good characteristics at NVH, the choice of slot/pole should be considered the mode number at least 4. For this case, the original design choose 42/8, the better choices closed to 42/8 are 48/8, 54/8, 60/8. The mode number of 54/8, however, is 2. As a result, we choose 60/8 because of its LCM. See the rotor displacement of one circle, 60/8 has smaller force variation than 48/8.

3.2 Motor design

CPEV motor specification is shown as table 1. We have four targets for new design:

A. Solve the NVH problem
B. Keep the motor performance
C. Keep or raise power density
D. Keep or raise efficiency

Table1: CPEV motor performance

Gen1 CPEV motor	performance
Max. Power	70 kW
Max. Torque	210 Nm
Max. speed	8000 rpm
Stator outer diameter	260 mm
Length(stator)	90 mm
Max. system eff.	94%

Before detail motor design, there are two new design limits. One is that slot/pole shall be 60/8, another is that stator outer diameter shall be 250 mm for a stronger structure. Motor design and analysis process is shown as Fig. 4. New design requirements are to keep similar back emf and reduce motor volume. The motor torque equation is shown as equation(4). It means that the torque constant and back emf constant should be the same.

$$T = \frac{m_1}{\sqrt{2}} P N_1 k_w \emptyset_F I_a \quad (4)$$

After motor design, main design parameters are shown as table 3. To get the better design value, we used DOE (design of experiment) method to do the sensitivity analysis. The motor design results are shown as table 4. The optimized motor efficiency map analysis plot is shown as Fig. 5.

Table3: Comparison of Gen1 and Gen2 design

	Gen1	Gen2
Slot/pole	48/8	60/8
Diameter	260 mm	250 mm
Parallel	2	4
Turn	4	5
Results		
Back emf@3000 rpm	160 V	143 V
Slot fill	46 %	49.7 %
Resistance	26.7 mΩ	17.7 mΩ

Table4: design value of sensitivity design

	Before DOE	After DOE
Slot opening	2.5 mm	2.75 mm
Bridge width	3 mm	3.3 mm
Stator inner diameter	170 mm	168.8 mm
Stator inner diameter	86 mm	88.97 mm
Yoke width	19 mm	19.8 mm
Teeth width	5.4 mm	5.84 mm
results		
Efficiency	94.448	94.69
Torque	179.378	190.62

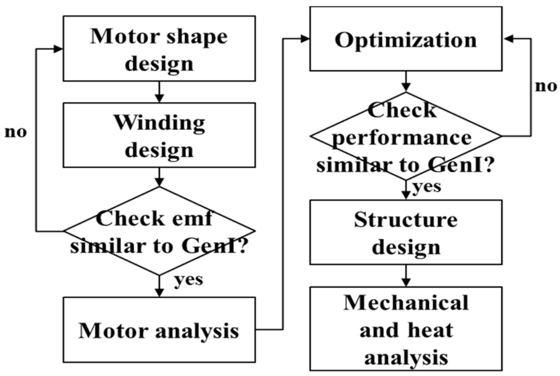


Figure4: motor design process

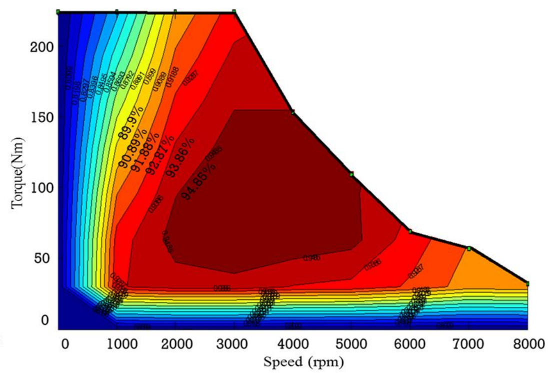


Figure5: motor efficiency map (analysis)

4 Experiment and validation

Gen2 motor prototype test platform was built to measure torque, speed, efficiency, and the like. Motor efficiency map is shown in fig. 6. Finally we did the road test for CPEV NVH(fig. 7). We measured the vehicle interior noise as illustrated in Fig. 8. Interior noise was reduced around 15 dB at a speed of 20 km/h.

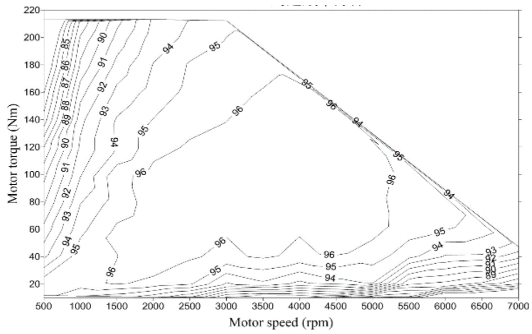


Figure6: motor efficiency(test)

Figure7: CPEV road test

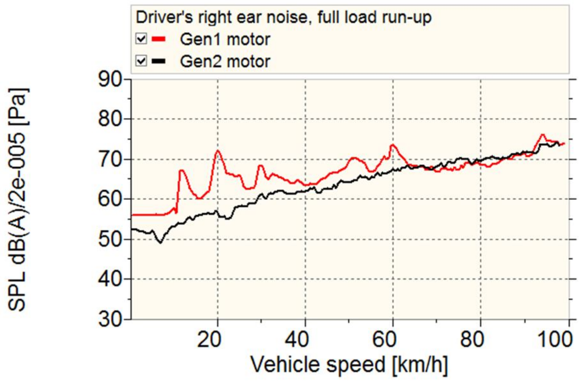


Figure8: Interior noise comparison for a CPEV equipped with refined motor against that of original motor

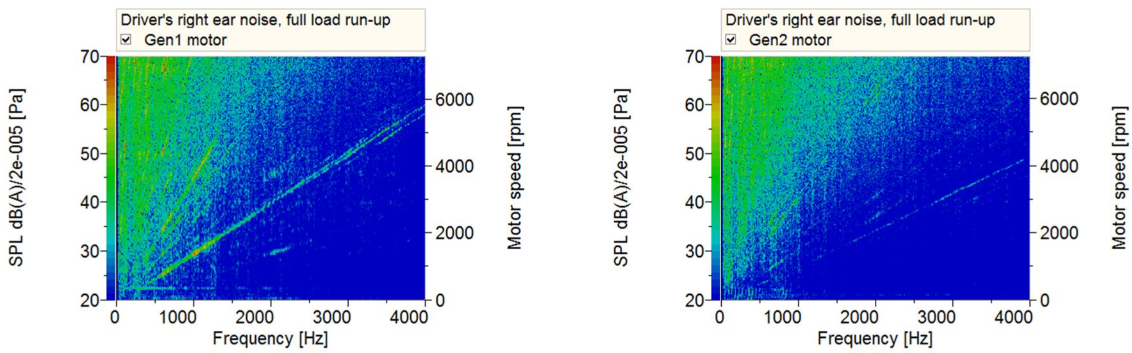


Figure9: Comparison of GenI and GenII noise in CPEV

5 Conclusion

For motor NVH characteristics, the noise and vibration source are usually dominated by motor electromagnetic force. But the normal force and tangential force should both consider when designing a motor. By choosing optimal slot/pole ratio, we can effectively reduce the motor noise and comply with pass-by noise regulation. Using FEM analysis tools can assure a right motor design and mitigate the potential NVH issue.

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