ABSTRACT

This paper presents a simple procedure for acoustic noise reduction in switched reluctance motor (SRMs). Radial forces between rotor and stator teeth cause a vibration of stator laminations and windings. The vibrations lead to acoustic noise. The radial forces can be determined by the two-dimensional finite element method (FEM). The magnitude of the acoustic noise at any operating speed is calculated by an analytical mode which depends on the radial forces and circumferential deflection. The calculation, simulation and measurement results are useful to improve stator and rotor poles with acoustic noise reduction. Moreover, it is important for the SRM to avoid the mechanical resonant frequency. If the electric frequency equals mechanical resonant frequency, the vibration and acoustic noise is extremely high and destroys the mechanical structure of the high speed motor.

I. INTRODUCTION

from automotive vehicles [1] to the aircraft engine areas. The SRM has been used as a starter/alternator for more electric aircraft [2-8]. However, a torque is maximized to speed up in starting mode and efficiency is maximized in higher speed by torque per RMS current.

The torque-speed characteristics are functions of the reference currents, turn-on and turn-off angles. They were determined by a dynamic SRM simulation in different speeds and control modes. In over a wide range of speeds, the maximized torque control can be achieved by current controller and optimization of choosing turn on-off angles. At low and medium speeds, the phase currents are controlled by discontinuous conduction mode DCM and at higher speeds by continuous conduction mode (CCM) to maintain torque values.

II. IMPACT TEST

Every electric motor has its own natural mode frequencies. They depend on the stator shapes, mass and material. The SRM stator is composed of silicon steel lamination, aluminum rings and copper windings. In order to investigate the frequency, an impulse excitation by a hammer impact was used to measure the natural frequencies of the motor in fig 1.

![Hammer impact setup (a) and SRM for test (b) [2]](attachment://hammer_impact_setup.png)

The impact test results are shown in fig 2. The plastic hummer was used to impact on the stator and the microphone was placed 1m from the impact point.
The frequency spectrum of the stator lamination and aluminum rings. It was noticed that the resonant frequencies of the aluminum water jacket are about 1.1 kHz and 2.6 kHz (Al mode2).

The resonant frequencies of the steel lamination are 1.9 kHz (ST mode2), 4.9 kHz (ST mode3) and 8.7 kHz (ST mode0).

The resonant frequencies were distinguished by a FFT analysis of the acoustic noise in Master thesis [2]. Those frequencies are very important to validate the mode frequencies of the SRM stator vibration forms as fig 3. This method was introduced for the acoustic noise model of electric motor in [10].

III. CALCULATION OF THE ELECTROMAGNETIC RADIAL FORCES

In the SRM, radial force is dependent on the flux density in the air gap. A 2D FEM model has been built to investigate the radial force vs current and rotor position is fig 4a,b.
IV. ACOUSTIC NOISE CALCULATION

The magnitude of the acoustic noise at any operating condition depends on the circumferential deflection due to the radial force density, which is the radial force per unit operating square. The analytical expression for the dynamic circumferential deflection for modes $m \geq 2$ can be expressed as (1) from an analytical model [9]:

![Fig. 4a: 2D FEM model](image)

![Fig. 4b: Radial force vs current and rotor position results.](image)

From a dynamic SRM model in [4, 5, 6], the radial force waveform can be obtained at different speeds in fig 5. This force is used to calculate the deformation and acoustic noise later.

![Fig. 5: Radial force waveforms vs rotor position at 30000 rpm](image)
where,

\[ D_{f \text{exc}} = \frac{12 F_{m(f \text{exc})} R_m}{m^4 E} \left( \frac{R_m}{h_s} \right)^3 \]

\[ \left[ 1 + \left( \frac{f_{\text{exc}}}{f_m} \right)^2 \right] + \left[ \frac{\delta f_{\text{exc}}}{\pi f_m} \right]^2 \]

\[ m \text{, } f \text{, circumferential mode number and mode frequency; } \\
E \text{, module of stator material elasticity; } \\
R_m \text{, mean radius of stator yoke; } \\
h_s \text{, stator pole height; } \\
f_p \text{, fundamental frequency of phase current (Hz); } \\
f_{\text{exc}} \text{, excitation frequency (Hz); } \\
\]}

The harmonic radial forces and their frequencies have been determined by a FFT analysis of the radial force waveforms as depicted in fig 6. The harmonic order 1 was defined 100% and the other less than 70% are displayed in fig 6.

![Fig. 6Radial force harmonics and their frequencies, fundamental frequency of 2000 Hz](image)

The deformation was calculated by radial force waveforms at different speeds and modes [9].

![Fig. 7Deformation vs harmonic frequencies.](image)
Sound power radiated by an electric machine can be expressed as (2) in [9]:

\[
P = 4 \cdot \sigma_{ref} \cdot \rho \cdot c \cdot \pi^3 \cdot \left( \frac{f_{exc}}{2 \pi} \right)^2 \cdot D_{stk}^2 \cdot R_{stk} \cdot L_{stk} \tag{2}
\]

where,

- \( P \): radiated sound power (W);
- \( \sigma_{ref} \): relative sound intensity \( \sigma_{ref} = k^2 / (1 + k^2) \);
- \( k \): wave number \( k = (2 \cdot \pi \cdot R_{out} \cdot f_{exc}) / c \);
- \( c \): traveling speed of sound (m/s) in the medium;
- \( \rho \cdot c \): specific heat of sound (J/kg·s·m) for air density;
- \( R_{out}, L_{stk} \): outer radius and stack length of the stator (m).

The sound power results have been calculated in fig 8. The mode 2 has a highest sound power at 1.9 kHz frequency corresponding to the motor speed of 27,000 rpm.

![Fig. 8 Sound power vs excitation frequency](image)

Depending on the threshold of human ear sensation, the reference of sound power level is well known. Consequently, the acoustic noise power level in decibels becomes:

\[
L_{sw} = 10 \cdot \log \left( \frac{2 \cdot P}{P_{ref}} \right) \tag{3}
\]

With, the reference sound power level \( P_{ref} = 10^{-12} \text{W} \)

![Fig. 9 Sound power vs excitation frequency](image)

The sound level are extremely high at different mode in a wide frequency. With Mode 2, the sound level is about 110 dB at the frequency of 1.9 kHz. From this analysis, the electric frequency of SRM is not equal 1.9 kHz (27,000 rpm). Because the resonance problem happens and they can destroyed the mechanical structure.
V. SRM SOUND LEVEL MEASUREMENTS

The magnitude of acoustic noise depends on many factors such as magnetic radial force, mode shapes and stator damping. The peak acoustic noise corresponds to the maximum deflection of the stator for the dominant circumferential mode frequencies and modes.

In order to determine the noise level at very high speed of the SRM, the digital noise meter was used to measure at different constant speeds. The test bench of the noise level and spectrum has been built in fig 10. The noise was measured at no-load test to remove the influence of the radial force noise.

![Fig 10 The test bench for sound level measurement](image)

The test bench was isolated from surrounding environment to remove undesired noise. Moreover, at very high speeds, the mechanical components can fly away due to radial forces or unbalance mistakes. The measurement condition includes a sandbag box and microphone installed inside box with 1m from motor in underground, there was no motor or other machine run at that time.

<table>
<thead>
<tr>
<th>Speed (rpm)</th>
<th>Electrical Frequency (Hz)</th>
<th>Noise Level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>333</td>
<td>70</td>
</tr>
<tr>
<td>10,000</td>
<td>667</td>
<td>88</td>
</tr>
<tr>
<td>15,000</td>
<td>1,000</td>
<td>90</td>
</tr>
<tr>
<td>20,000</td>
<td>1,333</td>
<td>112</td>
</tr>
<tr>
<td>25,000</td>
<td>1,667</td>
<td>113</td>
</tr>
<tr>
<td>35,000</td>
<td>2,333</td>
<td>115</td>
</tr>
<tr>
<td>40,000</td>
<td>2,667</td>
<td>114</td>
</tr>
<tr>
<td>43,000</td>
<td>2,866</td>
<td>120</td>
</tr>
<tr>
<td>47,000</td>
<td>3,133</td>
<td>112</td>
</tr>
</tbody>
</table>

The acoustic noise resonant frequencies have been determined in fig 10 at different speeds from 10,000rpm to 40,000 rpm.
The table 1 shows the noise level vs speed. The noise values are very high up to 120 dB at 43,000 rpm. However, it is reduced at 47,000 rpm due to avoid the mechanical frequency resonance. The switched reluctance motor was operated at no-load, so the radial magnetic forces which depend on the phase current and flux density has no significant influence on the measured results. The noise source is only from the mechanical vibration.

The precision of the sound level measurement was effected by microphone and analyzer. The sound level has been measured with the frequency from 0 to 20 kHz.

VI. CONCLUSION
The acoustic noise level has been measured with speed up to 47,000 rpm and the noise spectrum frequency was analyzed for different speeds. To improve the acoustic noise performance of the SRM, there were some proposals of changing the shape of the stator or rotor teeth. To reduce the radial force, the corners of the stator teeth have changed to round shape to decrease the radial force. The stiffness of the stator yokes was increased to reduce the deformation of the stator. A detailed analysis of the modified shapes was done in [3]. Due to the rotor has salient poles, the air-gaps between rotor teeth and slots are not equal and the high velocity of the air blocks in rotor slots can create the acoustic noise significantly. To reduce this part of the acoustic noise, the rotor slots can be filled by plastic material.

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VIII. REFERENCES
BIOGRAPHIES

Minh Dinh Bui received the B.S. degree in electrical engineering from Hanoi University of Technology, Vietnam, in 2003 and the M.Sc. degree in the Department of Electrical Engineering from Hanoi University of Mining and Geology, Vietnam, in 2007.

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