LOW VIBRATION DESIGN OF SRMS FOR AUTOMOTIVE APPLICATIONS USING MODAL ANALYSIS

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Abstract:
The search for low noise SRM designs, has encouraged this research to focus on the effects of different lamination shapes on vibration. Five different shapes are considered, with one emerging as the best candidate for the 12/8 pole combination considered. The implications of using different phase numbers in the design are also explored from a vibration and noise point of view.

I. INTRODUCTION

The acoustic noise produced by stator vibrations in switched reluctance motors is a serious disadvantage for industrial applications. It is widely accepted that the radial force acting on the stator of the motor is the dominant source of vibration and acoustic noise in a well-manufactured SRM [1–4]. The attractive force between the stator and rotor of the machine, which tends to deform the stator yoke, suddenly decreases with decay of the phase current during commutation, resulting in elastic vibrations. This phenomenon has been validated by accelerometer tests [1,3,4]. The stator deformation corresponds mainly to the second or fourth order mode shape of the stator yoke, with significant noise emitted at natural resonant frequencies of the stator assembly [1,4,5]. Obviously, a stator with a high stiffness, can help reduce vibration deformation. Low vibration and noise can be achieved by mismatching the waveforms and frequencies of the excitation force with the stator mode shapes and resonant frequencies of the SRM. Electronic techniques for noise reduction include random pulse width modulation (RPWM) [6] and active noise cancellation techniques [3]. Because the resonant frequencies of the stator have to be known or measured before implementing electronic techniques, an accurate determination of the natural frequencies and their corresponding mode shapes is essential in vibration control of the SRM drive.

The resonant frequencies and mode shapes of the SRM can be obtained by analytical calculation [2,4,5,7], numerical computation, usually by the finite element method [2,4,5,8–10], and/or experimental techniques [1,4,5,7,9]. Experimentation can be performed only after manufacturing a prototype motor. Therefore, there is considerable advantage and interest in using numerical methods for the computation of resonant frequencies and mode shapes during motor design. The simplifications in the analytical model may cause unacceptable errors. The conventional round stator stack has been analyzed at depth, including the fillets at the pole root [5,9], the shape and size of the pole [10], the length and thickness of the yoke [2,4], and various frames [4,5]. In this paper, the effects of different shapes of the stator laminations and frame are examined, which is a new contribution to low vibration motor design. Five different geometrical topologies of stator stacks are considered.

II. NUMERICAL MODELS OF THE SRM STATOR FOR MODAL ANALYSIS

The stator of a traditional SRM with 12/8 poles is used as a prototype to investigate modal vibrations, as shown in Model 1 of Fig. 1 (a). Based on the same copper, stator bore, stator pole length and the utilization of lamination steel, four other outlines of stator lamination stacks are derived. These stator configurations can be applied to SRMs with 2, 3, 4 and 6 phases although the two phase SRM can only be used for unique drives. The geometrical topologies and the corresponding finite element models are shown in Fig. 1. Two stator stacks have the same polygonal outlines but with different pole positions. The poles are arranged under the polygonal vertices in Model 2 in Fig.1 (b) while the poles in Model 3 are aligned with the sides of the polygonal lamination sheets, as shown in Fig.1 (c). For the lamination stacks with square outline, the difference in Models 4 and 5 lies in the positioning of the poles. Four of the poles are aligned on the sides of the square in Fig 1d as opposed to the corners as shown in Fig 1e. Fillets with the same radius are located at the pole roots in all five models of the SRM stator since it has been shown in [9] that they increase the stiffness of the stator.
A structural finite element analysis is performed on the five stator-stacks shown in Fig. 1 as well as for the stacks attached to smooth frames with a thickness of 10mm. Although a 3D finite element analysis is carried out, because of space limitations, only selected in-plane flexural mode shapes are given in this paper, as shown in Fig. 2.

The in-plane flexural modes play an important role in electromagnetic vibrations while the bending, torsional and out-of-plane flexural modes contribute to vibrations under unbalanced or fault situations. If a smooth frictional frame is added to the lamination stacks, the stiffness and modal frequencies of the combination increase.
Observing the computed results, the first 6 mode shapes are related to rigid motion of the lamination stack in all models, i.e., three displacements along the x-, y- and z-axes and three rotations around the three axes. The resonant frequencies in all five models increase with the order of the mode shapes, except for the 0th order mode. In models 1, 2 and 3 of Fig. 1, most mode shapes appear in pairs which have the same shape and frequency but a 90 degree phase difference, such as the 2nd order mode shape shown in the a and a’ rows for models 1, 2 and 3. Some modes of the same order have different resonant frequencies in models 4 & 5. For example, the 2nd order mode in Model 4 has frequencies of 2485Hz and 3556Hz, respectively, while the frequencies of the corresponding modes in model 5 are 2405Hz and 3705 Hz respectively. For most modes of the same order, the resonant frequencies of models 2 to 5 are higher than the modal frequencies of the traditional circular design of Model 1, except for the (g), (h) & (k) rows in Table 1.

Table 1. Comparison of the modal frequencies among different stator shapes

<table>
<thead>
<tr>
<th>Mode Ref. # in Fig. 2</th>
<th>Resonant frequencies (Hz) and relative variations (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model I</td>
</tr>
<tr>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>(a) 2nd</td>
<td>2141</td>
</tr>
<tr>
<td>(a’) 2nd</td>
<td>2141</td>
</tr>
<tr>
<td>(b) 3rd</td>
<td>5509</td>
</tr>
<tr>
<td>(c) Quasi-4th</td>
<td>9294</td>
</tr>
<tr>
<td>(d) 4th</td>
<td>N/A</td>
</tr>
<tr>
<td>(e) 5th</td>
<td>12413</td>
</tr>
<tr>
<td>(f) 6th</td>
<td>13643</td>
</tr>
<tr>
<td>(g) 0th</td>
<td>18662</td>
</tr>
<tr>
<td>(h)</td>
<td>23528</td>
</tr>
</tbody>
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This is more evident for the square models 4 and 5, which implies a higher stiffness for these two models. The pole deformation of the modes of the same order in different models can show differences from each other. For instance, the peak of the 2nd order mode shape lies behind the poles in models 1, 2 & 4 while they lie at the centers of neighboring poles in models 3 & 5. This is important for vibration analysis and measurement as well as low vibration design.

III. DESIGN SELECTIONS OF LOW VIBRATION SRMS

There are several guidelines to select low vibration designs: Firstly avoid electromagnetic excitations, which have waveforms similar to the mode shapes. Secondly mismatch the modal frequencies with the frequencies of possible excitation, or push the resonant frequency above the audible range if possible. Thirdly the square stack has a relatively higher resonant frequency of the second order mode shape, which the principal component of the magnetic force can excite. Hence vibrations of lower amplitude results, due to the higher stiffness. Based on the above, several design guidelines are given as follows:

1. Using the stator stack for a 2 or 3 phase motor, instead of a 6 phase motor, the order of the main components of the radial force waveform will increase from the 2nd order to the 4th order (for 3 phases) or 6th order (for 2 phases). The increase in the resonant frequencies with the order of the mode shape means that the stiffness of the stator increases and the vibrations will be reduced as the consequence. In addition, there is a larger range of excitation operational frequency before excitation of resonance. For the magnetic forces with the same amplitude, the 6th order waveform and 4th order waveform will produce a lower vibration than the 2nd order waveform.

2. If the five stator lamination stacks are used for a 6-phase SRM with 12/10 poles, the dominant mode shape will be the 2nd order. It seems that the normal square stack has the highest stiffness among the five candidates. If all of the 2nd order modes (Fig.2 (a1) & (a2), i=1,...5) are carefully examined, the mode shapes in Fig.2 (a2), (a4) & (a5) can only be excited under overlapping operation of two phases and the excitation forces in this case turn out to be small, especially in the leading phase. Thus the dominant excitation force with the lowest order, during turn-off of the conducting phase, may correspond to the seven other modes in the first two rows of Fig.2. Of these 7 modes, the sequence of ascending resonant frequencies is from Model 1 to 5. The selection of the lowest vibration for a 2 phase SRM should be from model 5 to 1.

3. If the stator stacks are used for a 3-phase 12/10 SRM with short flux-paths, the superior sequence for low vibration should be Models 4, 5, 3, 2 & 1 of Fig.1, respectively.

4. If the stator stacks are used for a 3-phase SRM with 12/8 poles, the lowest order waveforms of magnetic forces correspond to the modes in rows (c) and (d) of Fig.2. The best choice is still between the two stacks with the square outline, i.e., models 4 & 5 of Fig.1. The lowest frequency of Model 5 corresponding to the quasi-4th or 4th order modes is 13955Hz, which is the highest among the five candidates. Compared to the two lower order mode shapes of Model 5, there are three mode shapes related to quasi-4th and 4th order waveforms in Model 4, which may cause difficulties in noise control. Thus Model 5 is a better low vibration design.

5. If these stator stacks are used for 2 phase SRMs, the 6th order mode may play an important role in stator vibrations. In this case, the superior sequence for low vibration design is Model 4, 5, 3, 2 & 1.
There is no 0th order mode shape (i.e., expansion/contraction motion) in Model 4, which benefits low vibration operation. The rest of the models with ascending resonant frequencies at this mode are Model 3, 1, 2 & 5 in Fig.1.

For the modes related to tangential deformation shown in row (k) of Fig.2, the first 4 models have good stiffness, but Model 5 shows low stiffness.

A frictional mounting frame can increase the stiffness and resonant frequencies of most mode shapes in all five models, especially for the lower order modes.

IV. CONCLUSIONS

A modal analysis of five different stator lamination stacks with different shapes has been performed using three-dimensional structural finite elements. The effects of a smooth frame are examined for each case. The resonant frequencies and mode shapes of the five models are compared with each other. Criteria for low vibration designs are discussed for SRMs of different phase numbers. This will benefit the design selection of low vibration and low noise SRMs in industrial applications.

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REFERENCES


