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Research paper

A Switched Reluctance Motor with Lower Temperature Rise and Acoustic Noise

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Extended Abstract

Background and Objectives: One of the main drawbacks of switched reluctance motors (SRM) is high acoustic noise and significant research has been done to reduce it. In addition, reduction of temperature rise within the machine is usually considered as one of the most important goals of design. Therefore, a shape design method is introduced in the present paper for the SRM by which both heat transfer and acoustic noise are improved.

Methods: For evaluation of the proposed shape design method, a simulation model based on finite element method (FEM) is also developed to predict both the temperature rise within the machine and the produced noise. The simulation model is created using ANSYS finite element (FE) package and it is build up totally as a parametric model in ANSYS parametric design language. Since the convection heat transfer coefficients depend on the temperature rise, they are determined in the developed thermal model based on an iterative algorithm.

Results: The proposed shape design method is applied to a typical 8/6 SRM and simulation results including temperature distribution in various sections of the machine, displacement of stator and sound pressure level (SPL) are presented.

Conclusion: Based on the obtained simulation results, it is illustrated that the temperature rise and the noise of the SRM could be improved significantly using the introduced shape design method.

Introduction

Numerous attractive attributes of the SRM such as simple structure, high reliability and absence of permanent magnet/winding on the rotor makes it a viable candidate for motor drives in the different industrial applications [1,2,3] . Because of the excellent thermal dispersion characteristics in different parts of the SRM, special attention has been paid by the researchers on various design aspects of this motor. In spite of many advantages of the SRM, this motor produces high acoustic noise due to double salient structure of the machine. In order to reduce noise of the SRM, significant research works have been completed on the design of this machine in three recent decades. In comparison to works done on noise reduction of the SRM, less attention has been paid to thermal design of this motor. In addition, researches done in this area are mostly to introduce a thermal analysis/model for the SRM not to present a solution for reducing temperature rise within the machine.

Introducing electromagnetic and structural models based on FEM in [4], a stator structure for 6/4 SRM with less vibration and noise is proposed. In [5], a new design by special slot wedge referred to as structural stator spacers is introduced to reduce noise of the SRM. In [6], the effect of various structures of frame/ribs on the acoustic noise and vibration of a high-speed and high-power SRM is investigated. The effect of skewing the stator or/and rotor on the vibration reduction of the single-phase 6/6 SRM and three-phase 12/8 SRM is investigated in [7,8]. In [9], a simple design of a cylindrical outer shape rotor is introduced by which noise of the SRM is significantly reduced.

Thermal modeling of the SRM is complicated because it is not easy to calculate precisely core loss as a main source for heat generation. In addition, it is hard to determine accurately the convection heat transfer coefficients for different surfaces due to double salient structure of the machine. Based on FEM, a thermal analysis of the SRM is introduced in [10] in which the constant convection heat transfer coefficients are considered. A thermal analysis based on 3D FEM is described in [11] for the SRM in which the CFD analysis is used to determine the air velocity on inner surfaces of the motor required for calculating the convection heat transfer coefficients. In [12], a thermal analysis for the SRM based on 3D FEM is introduced in which the inside air temperature rise is predicted using a lumped parameter thermal model. A thermal model based on 3D FEM for double-stator SRM is introduced in [13] in which the air-gap is assumed to be a solid material with the same major properties as air such as thermal conductivity.

The main objective of the present paper is to introduce a shape design method for the SRM by which both temperature rise and acoustic noise are reduced simultaneously. To predict temperature rise within this motor required for evaluation of the suggested shape design method, a new thermal model based on FEM is also developed for the SRM. In the following, the proposed shape design method is described in next section. The thermal and structural models developed for evaluation of the shape design method are then introduced in the third section. To demonstrate the feasibility of the proposed shape design method, simulation results are then given for an 8/6 SRM. Finally, the paper is concluded in the last section.

The Proposed Shape Design Method

Because of copper losses, temperature rise in the windings is usually high and it can damage conductor insulation in a long time. Due to the significant volume of air surrounding the coils in the SRM as depicted in Fig. 1, the heat generated in the winding region cannot be transferred appropriately. In order to improve the heat transfer in the windings, this area can be filled by expanding stator yoke iron with the manner depicted in Fig. 2. Using this solution which is suggested as a patent by J. M. Stephenson [14], heat transfer from the windings to stator is done through conduction instead of natural convection and consequently heat transfer conditions will be much better. The extra iron placed between the stator poles has no effect on the electromagnetic characteristics because there is no magnetic flux in this area.

Regarding the noise of the SRM, the main reason for producing noise and vibration in this motor is the radial force applied to the stator poles from the rotor. In the most of research works done on design of the SRM for noise reduction, the machine structure is changed to improve the strength of stator. As an example, strength of the stator is increased in [5] by inserting some spacers between the adjacent stator poles as observed in Fig. 3. In order to demonstrate feasibility of this proposed idea, a prototype SRM is also constructed in this reference and it is shown that the noise of the SRM could be reduced significantly using the spacers.

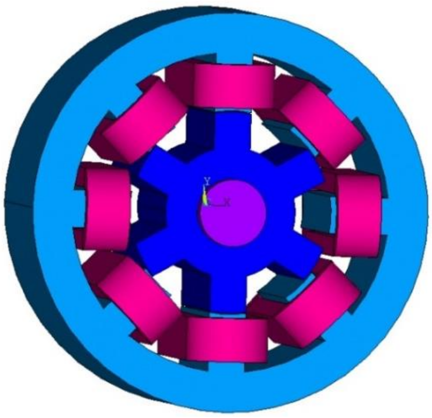
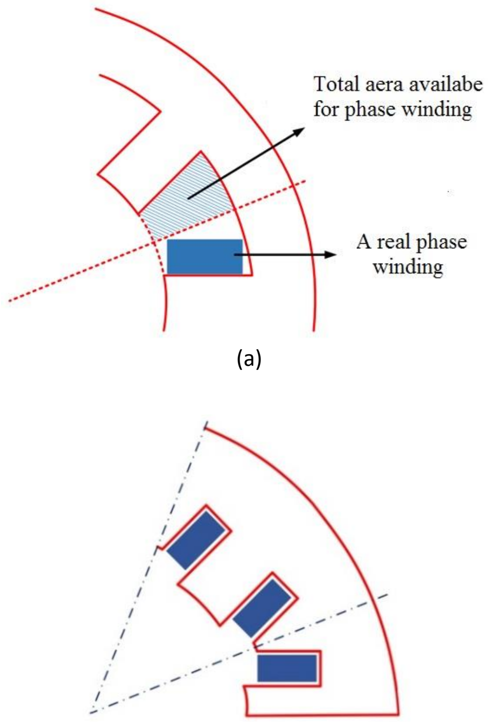


Fig. 1: The geometric structure of the SRM.



(a)

(b)

Fig. 2: Geometry of a stator slot: (a) total space available for putting the phase winding, (b) how to fill the space between the windings [14].

Filling the area between the coils with iron and inserting some spacers between stator poles, the structure depicted in Fig. 4 is suggested here for the SRM by which both temperature rise and noise could be improved simultaneously. As illustrated clearly from this figure, the suggested structure is suitable for the prebuilt windings. In addition, the considered barriers have no influence on the area available for the windings and they can be used instead of the slot wedges. To provide a high strength for the stator, it is suggested that the barriers are constructed from the ceramic.

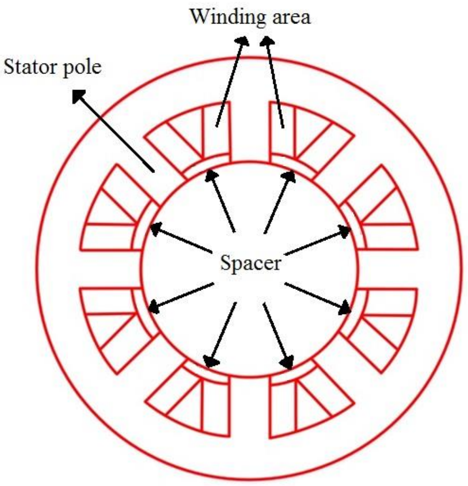


Fig. 3: How to put spacers between the stator poles in [5].

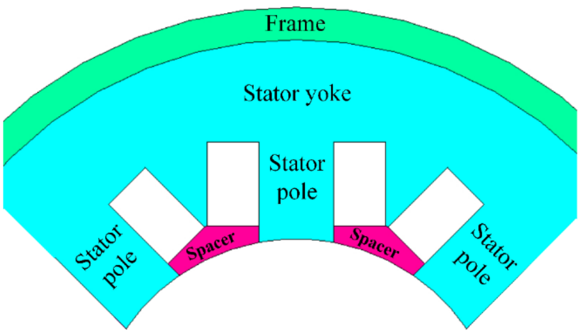


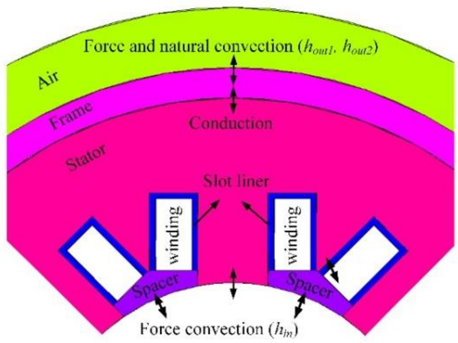
Fig. 4: How to insert additional iron and spacers between stator poles in the suggested structure.

Thermal and Structural Models

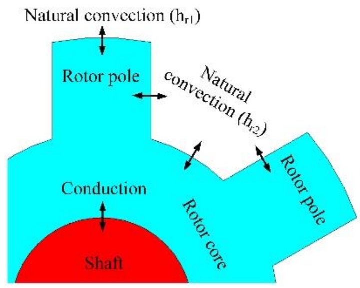
In order to evaluate the suggested structure, thermal and noise analyses are required and therefore the corresponding modeling is done in this section.

A. Thermal Modeling

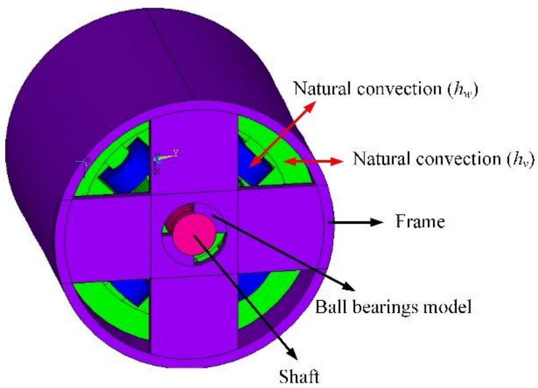
Using ANSYS FE package, a thermal model based on FEM is introduced here by which temperature rise in various parts of the SRM can be predicted. For thermal modeling, it is necessary to calculate first copper losses and core loss as the main sources of heat generation in the SRM. To do this, 2D FE transient analysis of the SRM is carried out and the phase current waveform and the flux density waveforms in different parts of the machine are predicted first. Having the instantaneous phase current, copper losses can be then calculated easily. Based on the improved Steinmetz equation, core loss is also derived from the predicted flux density waveforms. How to determine copper losses and core loss is explained elaborately in [15]. Due to rotor rotation and its salient structure, heat transfer through force convection is considered for inner surfaces of stator as observed in Fig. 5a. Both natural convection and force convection are also considered to model heat transfer from frame to the surrounding air. In addition, natural convection is assumed for heat transfer from rotor surfaces to air-gap as depicted in Fig. 5b. For all vertical surfaces of the machine including stator yoke, end-winding, rotor poles and rotor core, it is assumed that heat is transferred the surrounding air through natural convection as illustrated from Fig. 5c.



(a)



(b)



(c)

Fig. 5: Heat transfer: (a) stator, (b) rotor, (c) vertical surfaces.

The natural convection coefficients for horizontal and vertical surfaces are determined using (1) and (2), respectively [12].

$$h = \frac{k}{D}\left(0.6 + \frac{0.387R_{a1}^{1/6}}{[1 + (0.559/P_r)^{9/16}]^{8/27}}\right)^2 \quad (1)$$

$$h = \frac{k}{0.886D}\left(0.825 + \frac{0.387R_{a1}^{1/6}}{[1 + (0.492/P_r)^{9/16}]^{8/27}}\right)^2 \quad (2)$$

where:

$$R_{a1} = \frac{g\beta(T_s - T_a)D^3}{\nu\alpha} \quad (3)$$

$$R_{a2} = \frac{g\beta(T_s - T_a)(0.866D)^3}{\nu\alpha} \quad (4)$$

where h is the heat convection coefficient, D is the outer diameter of the stator yoke, k is the thermal conductivity of air, P_r is the Prandtl number, R_{a1} and R_{a2} are Rayleigh number, T_s is the surface temperature, T_a is the ambient temperature, β is the cubical expansion coefficient of air, α is the thermal diffusivity of air, v is the kinematic viscosity of air and g is gravitational force of attraction. Air properties are determined at the average temperature of ambient and surface using a linear interpolation of the data given in Table 1.

Table 1: Air properties [12]

Parameter	Value		
T (°C)	20	40	60
k (W/m/°C)	0.0257	0.0271	0.0285
v (10^{-6} m^2/s)	15.11	16.97	18.90
α (10^{-6} m^2/s)	23	25.87	28.81
P_r	0.713	0.711	0.709
β (10^{-3} /°C)	3.43	3.2	3

The forced convection coefficients for external surface of frame and inner surfaces of stator are derived as follows [12]:

$$h = \frac{k}{L} \times 0.664R_e^{1/2}P_r^{1/3} \quad , \quad R_e = \frac{Lv_f}{v} \quad (5)$$

where L is the length of air flow path and v_f is the velocity of the air flow.

In order to calculate the convection coefficient based on (1)-(5), we need the surfaces temperature and the surrounding air-gap temperature which are unknown. To solve this problem, the iterative algorithm shown in Fig. 6 is suggested in the developed thermal model. In this iterative algorithm, the convection coefficients and steady state temperature in various parts of the SRM are determined based on FEM. The thermal parameters used in the thermal analysis are given in Table 2 where the ambient air temperature is assumed to be 20°C.

Table 2: Thermal parameters

Different parts	Thermal conductivity (W/m/°C)	Specific heat (J/kg/°C)	Density (kg/m^3)
Stator lamination (iron)	20	438	7650
Copper	401	385	8933
Slot liner	0.076	1172	2150
Air	0.0263	1007	1.16
Frame (aluminum)	177	875	2770
Spacer	30	880	3900
Shaft (steel)	14.4	461	7817

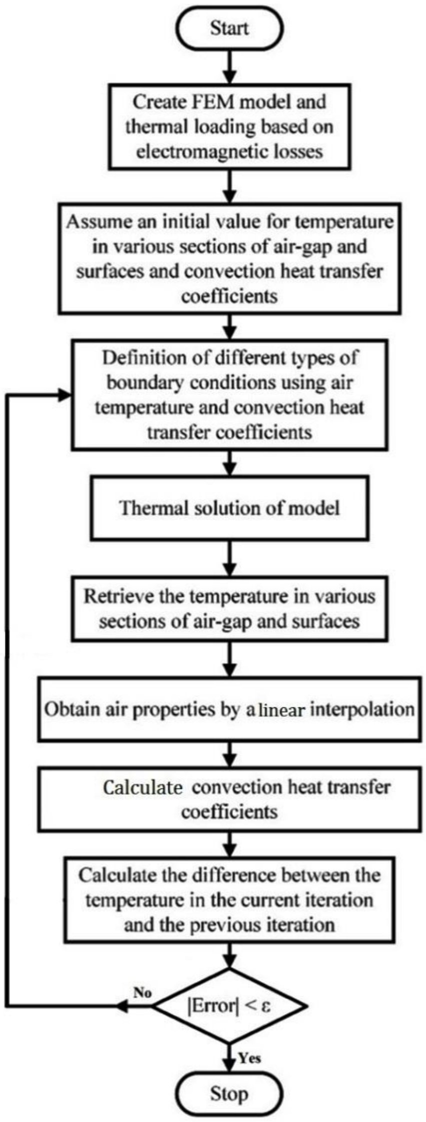


Fig. 6: Proposed steady state thermal analysis algorithm.

B. Structural Modeling

In order to evaluate the proposed shape design method described at above for noise reduction of the SRM, it is necessary to develop a structural model based on FEM by which stator vibration and sound pressure level (SPL) are determined. Attraction radial force between the excited stator pole and the adjacent rotor pole is the main reason for stator vibration and acoustic noise in the SRM. In the developed structural model, 2D FE transient analysis of the SRM is done to predict the instantaneous radial force acting on the stator pole. The manner for predicting this force is explained elaborately in [16]. The flowchart related to the developed structural model has been shown in Fig. 7 and the mechanical properties of the used materials are given in Table 3.

To carry out the proposed acoustic analysis, mass density and sound speed of the acoustic fluid should be known and these acoustic material properties for air are 1.21 kg/m^3 and 343 m/s, respectively. In the developed structural model based on FEM, the structural system is modeled by a set of appropriate finite elements interconnected at discrete points called nodes. The elements may have physical properties such as thickness, coefficient of thermal expansion, density, Young's modulus, shear modulus and Poisson's ratio. A transient structural analysis is carried out using the ANSYS mechanical solver. This type of analysis is used to determine the dynamic response of a structure under the action of any general time-dependent loads. Transient structural analysis is used to determine the time-varying displacements, strains, stresses, and forces in a structure as it responds to any transient loads. The time scale of the loading is such that the inertia or damping effects are considered to be important. If the inertia and damping effects are not important, a static analysis can be used instead.

Table 3: Mechanical properties [5]

Different materials	Young's modulus (N/m^2)	Poisson's ratio	Density (kg/m^3)
Stator stack (iron)	2.07×10^{11}	0.3	7800
Spacer (ceramic)	3.7×10^{11}	0.3	3900

Simulation Results

In order to evaluate the proposed shape design method described in the second section, it is considered for an 8/6 SRM, 1 kW, 1500 rpm with specifications given in Table 4 and the related simulation results are presented here. Using the developed thermal model, the winding temperature rise of the discussed 8/6 SRM at the middle of axial length of the machine is predicted for this operating point: phase voltage = 93 V, speed = 1000 rpm, turn-on angle = 10° and turn-off angle = 20°.

In this prediction, different convection heat transfer coefficients are considered for the frame (h = 5.5 W/m^2/°C for natural convection and h = 34.7 W/m^2/°C for the forced convection). For various iterations, this predicted temperature rise is shown in Fig. 8 and it is compared to that obtained for the discussed 8/6 SRM when the suggested shape design method is applied.

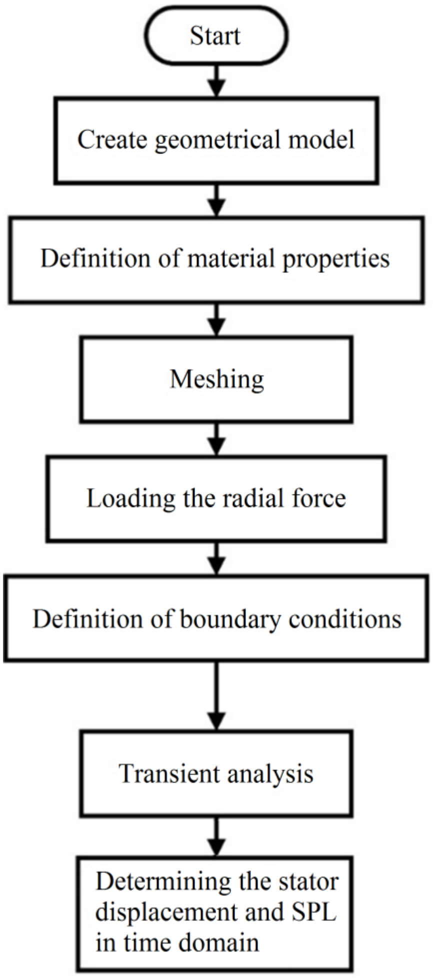


Fig. 7: The developed structural analysis.

Using the manner described at the first paragraph related to subsection A of the last section, core loss and copper losses are calculated for the considered operating point and they are 22.3 W and 25 W, respectively [15]. The comparison done in Fig. 8 is repeated for other parts of the machine and the results are summarized in Table 5. As seen from these comparisons, the temperature rise in different parts of the machine especially in the windings could be decreased significantly using the suggested structure (Fig. 4). Since rotor has no winding and there is no any permanent magnet in the structure of the SRM, this significant reduction of temperature rise is useful for preserving insulation of stator winding and therefore long-life of the machine is increased.

The temperature distributions predicted for the two structures are also compared in Fig. 9.

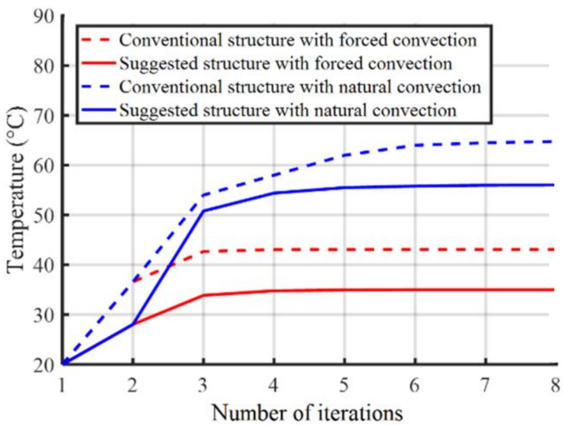


Fig. 8: Temperature rise in various iterations.

Table 4: Motor specifications [15]

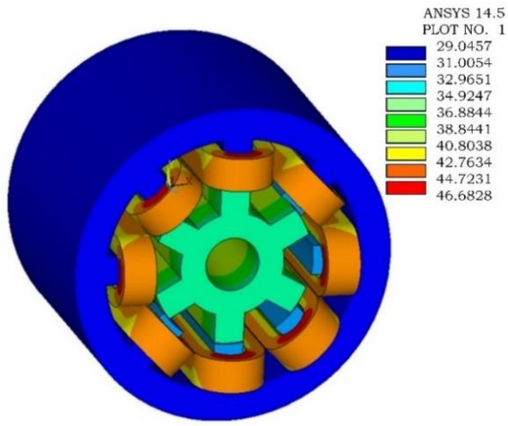
Parameter	value
Stator outer diameter [mm]	125
Stator slot-bottom diameter [mm]	100
Rotor outer diameter [mm]	63
Rotor slot-bottom diameter [mm]	41
Air gap length [mm]	0.35
Shaft diameter [mm]	21
Stack length [mm]	90
Stator pole arc [deg.]	21
Rotor pole arc [deg.]	21
Turns per coil	124
Resistance @ 20° C [Ω]	0.69

Table 5: Temperature in different parts of the machine

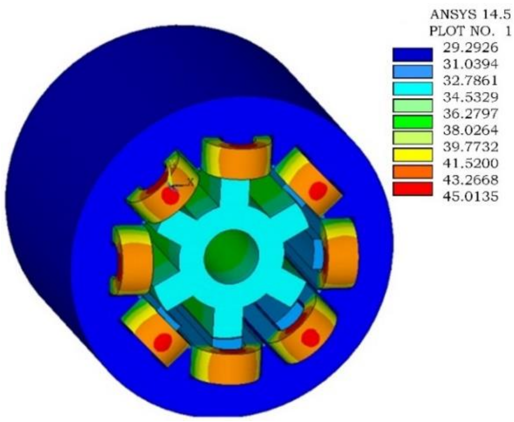
	Natural convection (h= 5.5 W/m2/°C)		Forced convection (h= 34.7 W/m^2/°C)	
Various parts	Conventional structure	Suggested structure	Conventional structure	Suggested structure
Stator yoke	51.8	51.1	29.9	29.8
Stator pole	53.3	52.1	31.5	31
Rotor pole	61.4	57.6	40.5	37.8
Rotor core	51.5	57.7	40.7	37.9
End-winding	56.4	56.2	46.1	44.5

To predict temperature rise in different times, dynamic thermal analysis should be done. Depending on the temperature, the convection heat transfer coefficients over different surfaces of the machine must be changed during the analysis. Carrying out 3D FE transient thermal analysis when the forced convection is considered for the frame, the winding temperature rise at the middle of axial length of the machine is also predicted for the conventional and suggested structures.

For the considered operating point, these predicted temperature rises are compared in Fig. 10 and it is illustrated that temperature rise is reduced significantly using the suggested structure. To predict each of the curves depicted in this figure, the computation time is about 12 hours on a 2.3 GHz Intel Core 2 with 10 GB RAM.



(a)



(b)

Fig. 9: Temperature distribution in the winding: (a) The conventional structure, (b) The suggested structure.

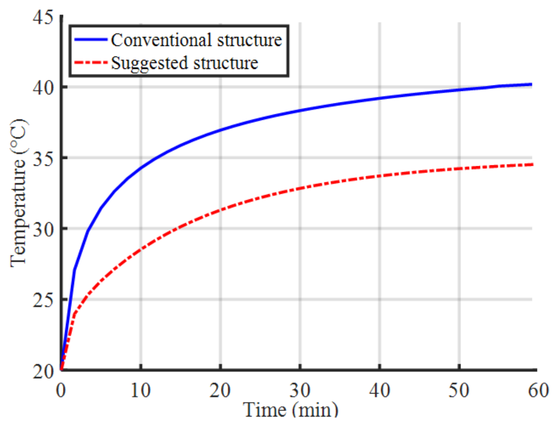


Fig. 10: Radial force acting on the stator pole.

As indicated at above, the main reason for noise and vibration of the SRM is radial force acting on the stator pole. In fact, this radial force is exerted on the excited stator pole from the adjacent rotor and it needs to be predicted for noise determination as done using FEM in [17]. Carrying out the 2D FE transient analysis using ANSYS FE package, the instantaneous radial force of the discussed 8/6 SRM is predicted for the considered operating point and it is shown in Fig. 11. For this predicted radial force, stator displacement and noise (SPL) of the discussed 8/6 SRM are determined using the developed structural model and the obtained results are illustrated in Fig. 12. These waveforms are also determined for the suggested structure (Fig. 4) and the related simulation results are given in Fig. 13. Comparing Figs. 12 and 13 shows that the noise and vibration of the discussed 8/6 SRM can be reduced significantly using the shape design method described in the second section.

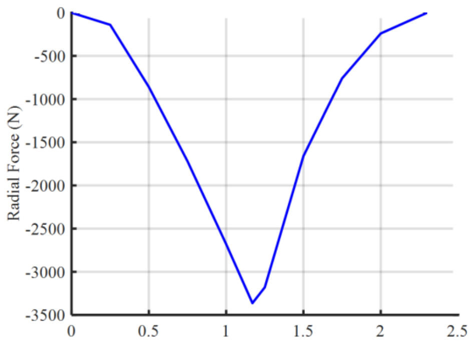


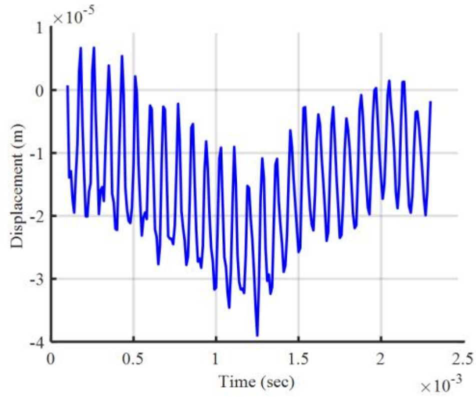
Fig. 11: Radial force acting on the stator pole.

It must be added that the produced noise is calculated in at 1 m distance from the machine. Using the developed simulation model, the modal analysis is also carried out for the discussed 8/6 SRM and the mode shapes predicted for the conventional and suggested structure are shown in Figs. 14 and 15. In the $mode_{m,n}$, m and n are the number of sinewave along the longitudinal axis and circumference of the stator yoke, respectively.

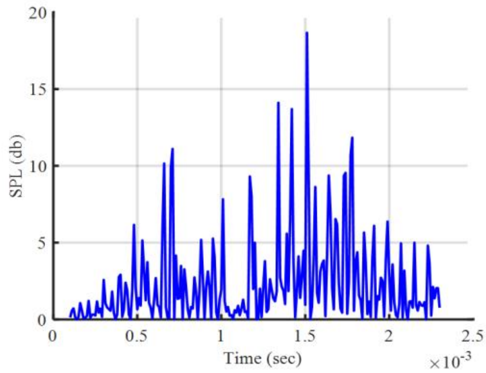
Maximum displacement of the conventional and suggested structure at various mode shapes are compared in Table 6. As seen from this Table, the maximum displacement (DMX) of the suggested structure at various mode shapes is reduced significantly.

Table 6: Maximum displacement (DMX) at various mode shapes

Mode shape	Conventional structure	Suggested structure
$Mode_{0,2}$	0.7022	0.6761
$Mode_{1,2}$	1.0084	0.9324
$Mode_{0,3}$	1.0317	0.9099
$Mode_{1,3}$	1.3176	1.2356

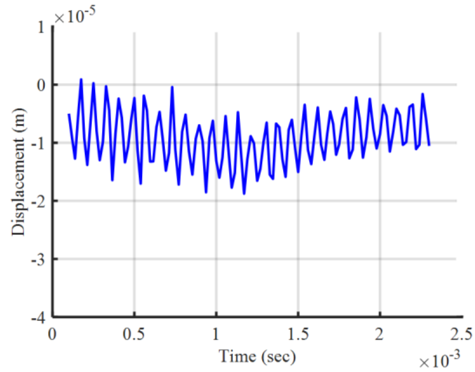


(a)



(b)

Fig. 12: The results obtained for the discussed 8/6 SRM: (a) displacement of the stator pole, (b) SPL conventional structure.



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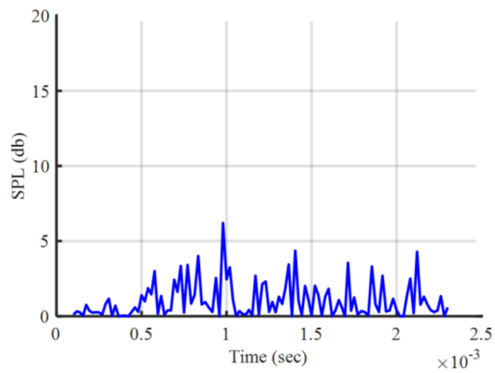

(b)

Fig. 13: The results obtained for the suggested structure: (a) displacement of the stator pole, (b) SPL conventional structure.

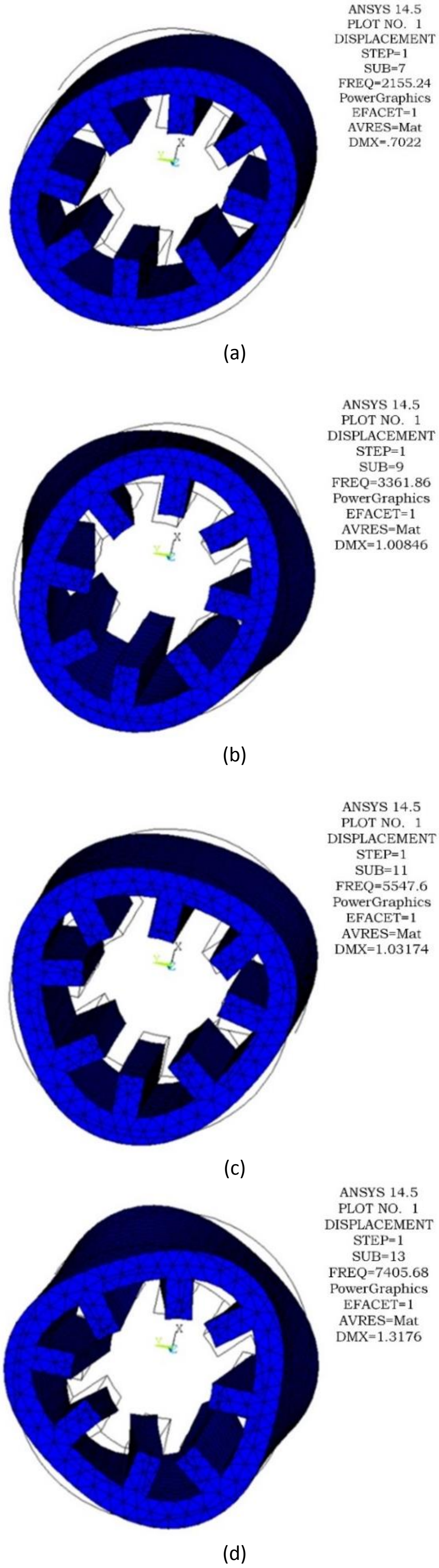

Fig. 14: Mode shapes and resonance frequency predicted for the conventional structure from modal analysis: (a) $\text{Mode}_{0,2}$, (b) $\text{Mode}_{1,2}$, (c) $\text{Mode}_{0,3}$, (d) $\text{Mode}_{1,3}$.

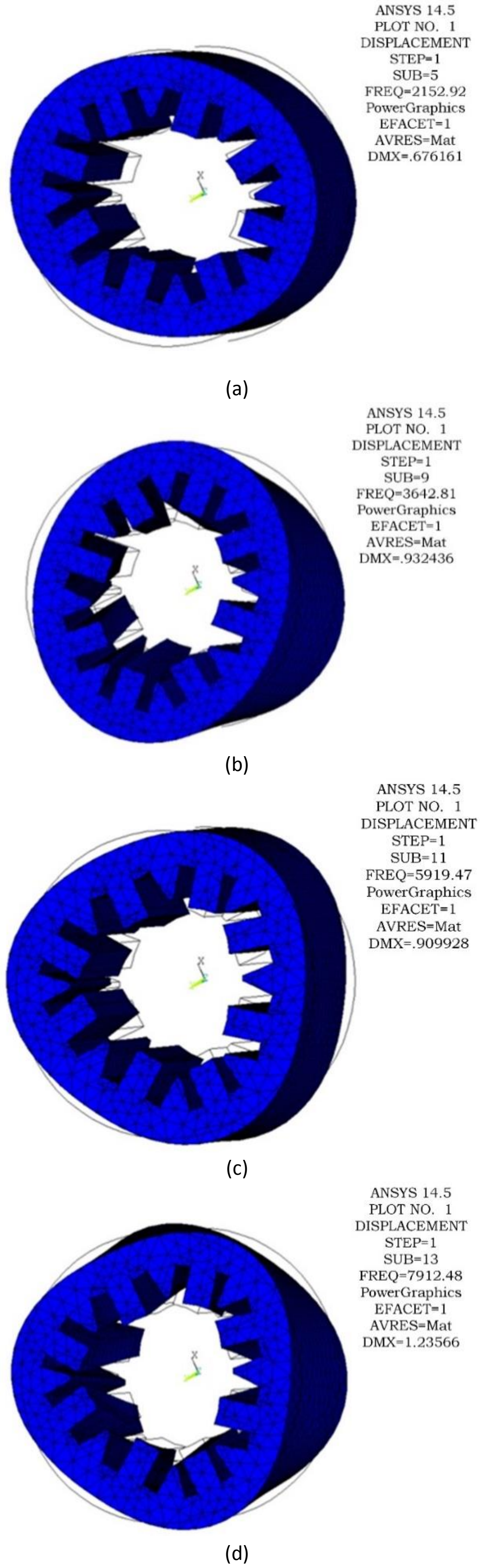

Fig. 15: Mode shapes and resonance frequency calculated for the suggested structure from modal analysis: (a) $\text{Mode}_{0,2}$ (b) $\text{Mode}_{1,2}$, (c) $\text{Mode}_{0,3}$, (d) $\text{Mode}_{1,3}$.

Conclusion

In order to improve simultaneously both the temperature rise and noise of the SRM, a shape design method was described. For evaluation of this shape design method, a simulation model based on FEM was also introduced for the SRM by which all necessary analyses including electromagnetic, thermal and structural were carried out. Using the developed simulation model, simulation results related to a typical 8/6 SRM were presented for two cases: (1) the conventional structure and (2) the suggested structure derived from the proposed shape design method. Comparing the simulation results for these two designs showed well effectiveness of the suggested shape design method for significant improvement of both heat transfer and noise in the SRM.

Author Contributions

The idea of the work was proposed by P. Vahedi and B. Ganji. The simulation model was developed by P. Vahedi and he also carried out the data analysis. B. Ganji interpreted the results and wrote the manuscript.

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Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

H	Heat convection coefficient
D	Outer diameter of the stator yoke
k	Thermal conductivity of air
R_{a1}	Rayleigh number
R_{a2}	Rayleigh number
T_s	Surface temperature
T_a	Ambient temperature
β	Cubical expansion coefficient of air
α	Thermal diffusivity of air
v	Kinematic viscosity of air
g	Gravitational force of attraction
L	Length of air flow path
v_f	velocity of the air flow

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