A FEM-BASED QUASI-STATIC NEURO-MODEL FOR ACOUSTIC NOISE IN SWITCH RELUCTANCE MOTORS

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Elimination of stator oscillations in electromotors is among the least studied, but important problems that can influence the electric performance, mechanical wear and tear and acoustical noise. In this paper, we focus on a switch reluctance motor (SRM) designed and prototyped for eventual production in Iran. The stator oscillation problems due to radial forces in SRMs have been reported as more acute as compared to similar motors. Due to the complicated mechanical and electrical structure of SRMs, obtaining any analytical model for its acoustical noise is quite impossible. This necessitates using numerical and experimental methods for obtaining an approximating model for acoustical noise. Since, off line simulation can be carried out, finite element (FE) analysis can be utilized so as to generate enough data for identifying a valid model. In this paper, we introduce a neuro-model with excitation current (amp) and position of stator (degree) as inputs and acoustical noise (db) as output. We performed two subsequent FE analysis using ANSYS package. Our first magnetic analysis is aimed at getting magnetic forces on the body of the stator and rotor, by exerting excitation current. In the second acoustical analysis, we give the magnetic forces, resulting from previous corresponding analysis, to the model and get the acoustical noise. We consider the acoustical behavior of the motor, in its inside and outside spaces, separately. Our approach is quasi-static, since we performed some FEM static analyses for approximating the dynamic behavior of the motor. Some simulation results of a acoustic noise in a designed SR motor, using our proposed model, is also given.

Keywords: Switch reluctance motor, electromotors, acoustical noise, neuro-model, finite element method, quasi-static approach.
1. Introduction

The switched reluctance technology, despite its rather long history, has attracted much attention in recent years and has become a serious contender for existing technologies for electromotor production. Its importance is much more pronounced in Iran, since its production is more feasible than other new approaches, like permanent magnet technology. SR motors have several advantages like lower cost and more ease of manufacturing, but also suffer from some drawbacks, the most important of which are torque ripple and acoustical noise.\cite{1,5,10} The elimination of torque ripple has been the subject of many important studies.\cite{11,12} The possibility of its manipulation via intelligent feedback control has been a main factor in reviving industrial interest in its design and manufacturing.\cite{9} However, several studies have shown that stator vibrations due to radial forces are as important, if not more so, in the production of acoustic noise and deterioration of the performance of the drive\cite{3,5} and some methods to reduce the oscillation of the stator are given.\cite{6} Rotor vibration and modal deflection is considered to be negligible,\cite{3} so we assume a perfect geometrical model for rotor and stator, in our analysis. The analysis presented in this paper, has been carried out, in conjunction with a comprehensive design effort, in order to deal with the scientifically less studied aspects of vibration and noise, alongside the better understood and already known procedures to reduce the torque ripple. Since, achieving an analytical model for the noise of SR motors is very cumbersome, using any numerical or experimental method in developing the model can be so appropriate, and some FE based analysis are performed to do this.\cite{7} Here, we focused our analysis on the mechanical vibrations of a specific 6/4 SR motor whose design procedure as well as intelligent torque ripple control procedures and implementation, has been reported elsewhere.\cite{8–10,13–14,16}

2. Model Development

As mentioned, we aim to obtain a model for acoustic noise of SRMs. Since, due to intricate nature of acoustic noise as well as complicate structure of SRMs, developing any analytical model for SRMs’ acoustic noise is impossible. An efficient alternative for this purpose is using any numerical or experimental method. In this paper, we used finite element method (FEM) as a powerful tool in numerical analyses in order to generate ample data and then train a neural network for learning their behavior. Our procedure of proposing the model is elaborated in the subsequent sections.

![Fig. 1. Motor magnetic model.](image)
2.1. Magnetic FEM analyses

The first part of our data generation procedure is concerned with magnetic finite element analyses. The general structure of SR motor magnetic model, we consider, is given in Fig. 1.

As observed in the Fig. 1, in magnetic analyses, we assumed two inputs and one output parameter. As reported in some studies, one of the main sources of acoustic noise is radial forces on the body of the stator and rotor. Generally, In the unloaded operating condition of a SR motor, the main forces exerted on the body of the rotor and stator, are magnetic forces, resulting from magnetic fields between rotor and stator. These magnetic fields, themselves, are generated due to the excitation current, applied on the stator poles. These are the main reasons, why we choose excitation current as one of the model inputs and magnetic forces on the body of the stator and rotor, as the model output. Since, we aim to model the dynamic behavior of the motor, the rotor angular position is also an input parameter for the model. For generality of our analyses, we attempt to cover a wide range of motor working conditions, so we varied the values of excitation current, from 2 to 30 amperes, by increments of 2 amperes. We varied, the values of rotor position from $0^\circ$ to $45^\circ$, by increments of $3^\circ$. The results can determine the full $0^\circ$–$360^\circ$ range for rotor positions via the geometric symmetries. Eventually, we will obtain results of 240 (15*16) distinct conditions of the motor. We have used ANSYS model, in our magnetic analyses, as given in Fig. 2. In our magnetic analyses, we ignore the coupling effects, means that at the time of exciting one pair of poles, the other poles are assumed to be unexcited. This is not the case in real applications, but simplifies the computational space of analyses noticeably, since it is shown that making this assumption, does not lead to any significant inaccuracy. So, we apply the excitation current to just one pair of poles. In ANSYS software package, for calculating the magnetic force, in a body, the body must be completely surrounded by a margin, and defined as a component. Defining the whole rotor and stator as two components and getting forces on them, is not so accurate for consequent procedures, since we aim to exert the values of these forces as inputs to the acoustic analyses. For obtaining, more realistic results, we partition the rotor and stator to some components, as each pole along side

Fig. 2. ANSYS magnetic model for the SR motor alongside its meshes.
regions in its vicinity, is defined as a component. Thus, we have 10 components in the whole model, to calculate magnetic forces in them. The results of magnetic forces are provided in the form of sum of forces in X direction and Y direction, separately. At the end of this unit, it is worth to mention that in this section, we have 16 magnetic analysis (correspond to each value of rotor position), in each of them, there are 15 distinct set of results. Each set of results of these very time-consuming analyses, is a 20-valued force vector (10 component*2 direction). Due to large space it takes, we ignore to give the results of magnetic force values in this paper. However, a descriptive configuration showing the locations and directions of the magnetic forces has been provided in Fig. 3.

2.2. Acoustic FEM analyses

We apply the magnetic forces, obtained from previous magnetic analyses, to acoustic model, so that it leads us to values of acoustic noise (in db). The general structure of acoustic model, we consider, is given in Fig. 4 and the model, used in ANSYS package, is given in Fig. 5.

The model, given in Fig. 5, represents the solid motor and the fluid in its internal and external, environments, alongside the meshes applied to it. Although, we considered, from the fluid elements provided by ANSYS package, only circles of radius 1 meter, around the motor, the results are correct in the presence of infinite environment. The direct result of acoustic analyses in the ANSYS is pressure gradients in the environment fluid, which by
assuming a reference fluid pressure, it can be mapped to the acoustical noise (in db), by the formula given in the (4.1).

\[ L_{sp} = 20 \log \left( \frac{P_{ref} + \Delta P}{|P_{ref}|} \right). \]  

(2.1)

We consider the maximum value of acoustic noise in the internal and external environments of the motor. The noise level inside the motor can be important when there are connections (e.g. heat transfer holes) between the two environments. The results of inside and outside acoustic noise in our motor are shown in Figs. 6 and 7, respectively. As observed in the figures above, there are some unexpected behaviors in the acoustic noises in the SR
Fig. 7. Outside acoustic noise as a function of excitation current (sorted in terms of rotor position).

Fig. 8. Situation for rotor position of 21°. The switching between poles is easily identifiable.

motors, that happen simultaneously in its inside and outside spaces. One of the worst cases occurs in the behaviors of noise of the motor, corresponding to rotor position of 21°. The abrupt transition in this rotor position can happen due to switching between the rotor and stator poles, as can be seen, in the Fig. 8, which corresponds to rotor position of 21°. The results of finite elements analyses, in some cases, may become inaccurate due to any singularity, stiffness, etc. The peak in the inside noise for rotor position of 21° is extremely dubious. For confirming this abrupt increase in mentioned plot, we generated two points in the vicinity of 12 amperes that the peak occurs in. We obtained the results of inside
A Fem-Based Quasi-Static Neuro-Model for Acoustic Noise

Fig. 9. Two modifier points around the peak in the inside noise for rotor position of 21°, corresponds to $i = 12$ amp.

Fig. 10. Inside acoustic noise as a function of rotor position (sorted in terms of excitation current).

acoustic noise, in the excitation current values of 11.5 and 12.5 amperes. As illustrated in Fig. 9, these results are in complete agreement to availability of peak in the 12 amperes.

The plots of Figs. 6 and 7 are the presentation of the results sorted in terms of $\theta$. The more applicable plots, can be obtained by rearranging the data of plots 5 and 6, to achieve
the inside and outside noise behaviors, sorted in terms of $i$, that are given in Figs. 10 and 11.

These plots can be assumed as acoustic noise of motor while being in rotation, under fixed excitation current. Up to this point, we have generated 242 results of different conditions for motor operation.

2.3. **Neural network training**

Having carried out the time-consuming finite element analysis for both force values and noise levels, we now have data sorted as $i$(amp), $\theta$(degree) and SPL(db), the first two constituting the inputs and the last constituting the output of the model we seek to identify. The structure of overall acoustic system for SR motor is illustrated in Fig. 12.

In this stage, we aim to train a neural network to obtain a satisfactory neuro-model for overall acoustical noise, illustrated in Fig. 12. The procedure for training the neural network is given in Ref. 15. The structure of the selected neural network topology is depicted in Fig. 13. The results of outputs of the trained neural network in comparison to real FE data, is shown in Figs. 14 and 15, for inside and outside acoustic noise, respectively.
So, at this stage, we are able to obtain the inside and outside acoustic noise levels of our SR motor, by giving the neural network, the rotor position and excitation current.

3. Noise Variation In A Complete Rotation Cycle

The ultimate purpose of this study is getting the acoustic noise in a specific switch reluctance drive whose design procedure is reported elsewhere. The current waveform has been determined by the adopted control strategy so as to track the desired speed, while maximizing the efficiency and minimizing the torque ripple. These profiles and waveforms
Fig. 15. Real FE data in comparison with neural network outputs, for OUTSIDE acoustic noise.

Fig. 16. (a) Speed variation, (b) position variation and (c) current waveform.

are illustrated in Fig. 16. Our designed SR motor is operating in the nominal speed of 3000 rpm and from Fig. 16(a), we recognize that the settling time of the motor is very small, about 0.35 s, that allows us to ignore the transient behavior of the motor. So we focus on achieving the acoustic noise of our motor, in the steady state condition, for one cycle. Since by having the values of excitation current and rotor position of the motor, we
Fig. 17. (a) Theta variation, (b) current waveform, (c) inside acoustic noise and (d) outside acoustic noise. All for a complete cycle of the motor in steady state condition.

can obtain the corresponding values of inside and outside acoustic noise, the results of this procedure is given in Fig. 17, for a one whole rotation cycle.

4. Concluding Remarks

This paper, mainly concerned with the acoustic sound of switch reluctance motors, since high acoustic noise level of SRMs is reported as main factor in hindering its broad applications. Achieving an analytical model for the noise of SR motors is very cumbersome, and any numerical or experimental method in developing the model must be utilized. In this study, we applied finite element method as a powerful numerical analysis. We generated some off-line data by magnetic and acoustic FE analyses using ANSYS package, and used them for training a neural network to obtain a model for acoustic noise of a specific SRM. We considered the noise for inside and outside spaces of the motor, separately. Our neuro-model was capable of getting excitation current and angular position of the rotor as inputs and resulting in acoustic noise. In other word, we approximated the dynamic behavior of the motor with numbers of quasi-static behaviors. Some simulation results, about the acoustic noise level of a specific motor, are given at the end of the paper. A major contribution of this work is to pave the way for direct analysis and optimization of the acoustic noise performance of electromotors. At present, the designers only try to shift the natural frequencies away from the audible range. Any attempt to control the noise level itself is only indirectly or not at all. Although there can be no general purpose lumped model for the generation of acoustic noise in all electromotors or at least all configurations of SR-motors,
the proposed method is general enough to be applicable to any production line of a motor with a particular configuration or any other device for that purpose.

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Appendix A

In this section, we give some of ANSYS modeling specifications we used in our acoustic analyses.

Element size

The length of the elements we used in meshing the model is 0.3 cm. The diameter of the structural model itself is 1.8 m and the region we considered the noise contours is a circle with radial 1 m around the structural model.

Element Types

Type number 82 (for the structural parts of the model), Type number 29 (for the environmental fluids with two different options, one for the fluids in contacting with the structural parts and one for the fluids without any contact with solid materials), Type 129 (for simulating the infinite environment around the model).

Material Properties

E=2e 11 & $\rho$ = 7000 & $\nu$ = 0.3 (the mechanical properties of the structural parts of the model), $\rho$ = 1030 & SONC=1460 (the acoustical properties of the environmental fluid).

References


