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Reduction of vibration and acoustic noise in permanent magnet synchronous motor by optimizing magnetic forces

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A R T I C L E I N F O

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A B S T R A C T

Two methodologies are proposed in this paper to reduce electromagnetic vibration and noise of permanent magnet synchronous motor. A multiphysics model is firstly established to predict the vibration and noise. Experimental tests are conducted to validate the model. Then, the source of the vibration and noise peaks from calculated and tested results is located. Two methodologies are proposed to mitigate this source. One is by reducing its amplitude through adjusting slot opening width and magnet shape. The other is by changing the phase of the specific force harmonic along the axial direction through stepwise or continuous magnet skewing. The optimum skewing angle is analytically derived. Based on the validated multiphysics model, optimizations under different methods are compared. It is found that considerable reductions of noise can be achieved by reducing low space harmonics of radial force. In particular, to reduce the noise over a wide frequency band, magnet skewing is a better solution than optimizing slot opening width and magnet shape.

1. Introduction

The electromagnetic vibration and noise of permanent magnet synchronous motor (PMSM), which are induced by electromagnetic force on the inner surface of stator, have gained much more attention in recent years [1–3]. Especially for fractional slot concentrated winding (FSCW) motor, the vibration and noise problem is quite outstanding due to its low space harmonics of radial force [4,5]. In domestic and automotive applications, the vibration and noise level is now a critical index to assess electric machines. Therefore, vibroacoustic optimization is necessary to acquire quieter performance.

Theoretically, vibration and noise reduction could be achieved by optimizing either intrinsic property of structure or electromagnetic force. The structural optimization is aimed at avoiding resonance by adjusting modal frequencies. In Ref. [6], the effect of some design parameters on modal frequencies is investigated. Eventually, stator skewing is employed to change stator frequencies to reduce the total noise of an induction machine. Response surface methodology is adopted in Ref. [7] to analyze the modal frequencies under different stator parameters. A noise reduction of 4.1 dB is available since the resonance is avoided. However, in variable speed application, structural optimization is aimed to increase the modal frequency, which generally results in a thick yoke. This will increase the cost and decrease the power/torque density. Moreover, electromagnetic force is wide-band excitation in variable speed applications, especially when current harmonics and rotor eccentricity are

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considered [8], which makes it difficult to avoid resonance since force frequencies become richer. As to the work of electromagnetic force optimization, switching frequency and control method are investigated to reduce the noise from high-frequency current harmonics in Refs. [9,10]. In design process, appropriate selection of slot-pole combination can considerably reduce the total noise [11–13]. However, this selection is generally limited by other performance requirements. When control method and slot-pole combination are determined, some other work can also be done to reduce vibration and noise. In Ref. [14], slot opening width (SOW) is optimized to mitigate noise of the end belt in an external rotor PMSM. With the spatial characteristics of radial force into consideration, this method could be improved to reduce the noise of the stator, which will be illustrated in this paper. In Ref. [15], noise test is conducted to locate the dominant noise peak. Then, rotor shape is optimized to reduce the force harmonic with the peak frequency and total noise could be reduced by 2 dB. In the similar way, stator slot, magnet and rotor slot are adjusted to lower the amplitude of the force harmonic which has the same frequency as the vibration or noise peak in Refs. [16,17]. However, in Refs. [15–17], only the force harmonic in a certain spatial point is reduced and the spatially distributed characteristics of electromagnetic force are ignored. It is found in Refs. [11–13] that lower space harmonics produce larger vibration and noise. Thus, both spatial and temporal characteristics of the force harmonic should be considered for better vibroacoustic improvement. Slot skewing and magnet skewing are respectively employed in Refs. [18] and [19] to reduce the responsible force harmonic for the noise peak. But in these two researches, the distributed force on a tooth surface is equivalent to single concentrated force acting on the tooth center, which could induce considerable errors around modal frequencies [20]. Moreover, the effect of slot skewing on stator modes should also be carefully considered when it is adopted to reduce force harmonics, since stator skewing greatly changes modal frequencies [6].

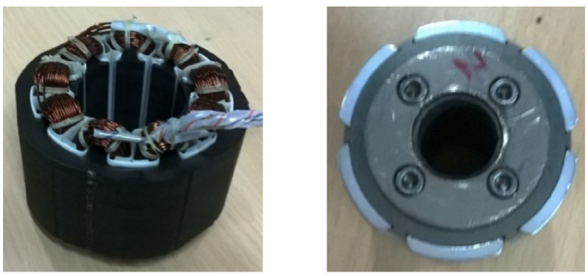
Two novel methodologies are proposed in this paper to achieve a better reduction of vibration and noise. One is by reducing the lowest space harmonics of radial force which have the same frequencies as the vibration/noise peaks. Particularly, both space order and frequency of force harmonics are taken into account to determine the corresponding field harmonics. SOW and magnet fillet radius are adjusted to attenuate these harmonics. The other is by changing the phase of the force harmonics along the axial direction to cancel their contribution to the vibration. To achieve this, stepwise and continuous skewing are proposed. Moreover, the optimum skewing angle is analytically derived. Finally, these two methodologies are compared based on the validated multiphysics model and the results show that they can both effectively reduce vibration and noise of PMSM.

2. Multiphysics modeling and experimental validation

In order to compare different optimization methods, an accurate multiphysics model is necessary for vibration and noise prediction. The motor used in this research is a FSCW PMSM with parallelly magnetized magnets, which is used in a compressor. This motor is shown in Fig. 1 and its main parameters are listed in Table 1.

Each step of multiphysics modeling is illustrated in Fig. 2. Firstly, a 3-D electromagnetic finite element (FE) model is built to calculate the force on the teeth surface. The tangential force on the teeth tips are also taken into account. Then, the structural model of stator is established and modal test is conducted to validate the model. It is noted that since the force mainly acts on the teeth surface, the arrangement of the surface nodes in electromagnetic mesh and structural mesh are the same to decrease the error induced by the interpolation. The calculated modes are compared with those from test in Table 2. Errors of modal frequencies are all below 5%, which indicates the accuracy of the structural model. Next, modal analysis considering the actual restraints of the test rig is performed. After the electromagnetic force is transferred from electromagnetic mesh to structural mesh, modal superposition method (MSM) is employed to calculate the surface vibration. Finally, boundary element method (BEM) is used to predict the noise. The spherical field point mesh shown in the figure is built to observe the spatial distribution of acoustic field. Both calculated vibration and noise are validated by the experimental results.

In the multiphysics modeling, three commercial softwares are used. The electromagnetic, structural and acoustic model are respectively established in Jmag, Ansys and LMS Virtual.lab.



a) b)

Fig. 1. The structure of the motor. a) Stator; b) Rotor.