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Magnetically induced rotor vibration in dual-stator permanent magnet motors

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ABSTRACT

Magnetically induced vibration is a major concern in permanent magnet (PM) motors, which is especially true for dual-stator motors. This work develops a two-dimensional model of the rotor by using energy method, and employs this model to examine the rigid- and elastic-body vibrations induced by the inner stator tooth passage force and that by the outer. The analytical results imply that there exist three typical vibration modes. Their presence or absence depends on the combination of magnet/slot, force's frequency and amplitude, the relative position between two stators, and other structural parameters. The combination and relative position affect these modes via altering the force phase. The predicted results are verified by magnetic force wave analysis by finite element method (FEM) and comparison with the existing results. Potential directions are also given with the anticipation of bringing forth more interesting and useful findings. As an engineering application, the magnetically induced vibration can be first reduced via the combination and then a suitable relative position.

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1. Introduction

Compared with conventional PM motors, dual-stator motors possess higher torque and power density and more flexibility for winding connections [1]. While magnetic force and vibration have been well studied for single-stator motors, it remains to be seen what they are for dual-stator case. This work is centered on the effect of the magnet/slot combination and the relative position between the two stators on rotor vibration.

Many researchers examined the relationships between the magnet/slot combination and unbalanced magnetic force and cogging torque of conventional motors [2–14]. Recent years, forces in dual-stator motors have drawn interest [15–22]. Liu et al. [15] identified the connections between cogging amplitude and stators' relative position by using energy method, based on which they proposed a method to suppress the cogging via altering the angle. Liu et al. [16] quantitatively examined three types of motors and well compared their cogging levels. Niu et al. [17] proposed a new multi-pole motor and achieved lower cogging. Diryak et al. [18,19] presented an optimum design for a kind of novel motor, and numerically compared the coggings for different magnet/slot combinations, and they also studied cogging minimization through two

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equivalent sub-motors. Kowalczyk et al. [20] made a comparison between dual-rotor and dual-stator motors having various basic parameters. Also, Qu and Lipo [21] and Djebarri et al. [22] examined such motors.

Previous studies paid much attention to the magnetic forces, but it seems that this vibration has not been well addressed especially by using analytical technique. Difficulties could be encountered when seeking analytical findings due to the complex structure and force. Since the motors are characterized as symmetric topology with moving loads [29], one can make full use of the symmetry to help capture vibration nature. Motivated by the similarities between power-transmission systems [23–26,31–33], authors of this work proposed superposition and modulation methods to deal with the typical rigid-elastic vibrations of conventional motors [11,12]. Also authors employed the superposition method to address the typical vibration by incorporating cyclic symmetry [27]. This method is mathematically effective, and it can find application in dual-stator motors, though it cannot quantitatively present more results. Even so modifications need to be made to handle the complex structure and forces upon the three concentric components. Because of this, other methods, such as analytical method, FEM, and suppression techniques [30], need to be combined to achieve more quantitative findings.

As well known, the dual-stator topology can reduce harmful magnetic forces because the design flexibilities can create more force neutralization, such as by suitable magnet/slot combination and relative position between the two stators, but few analytical findings especially on the relative position can be found in this respect. This work focuses on the effect of basic parameters, including the magnet/slot combination and other structural parameters, and especially the relative position, on the magnetic forces and rotor's vibration. Given the structural and force complexes, the scope is limited to the lower speed motors such as the direct drive one. Main findings are obtained by analytical derivation and verified by comparison with those from superposition method [12,14] and FEM.

2. Theoretical modeling

2.1. Model description

Fig. 1 illustrates a schematic of a dual-stator PM motor and an inertia frame $o-r\theta z$. The rotor is rotating at the speed of Ω , and its tangential and radial support stiffnesses are designated as k_t and k_r (not shown). Without any loss of generality, assuming the first magnet is attached at $\psi_1 = 0$ such that the p th ($p = 1, 2, 3, \dots, N_m$) is at $\psi_p = 2\pi(p-1)/N_m$, where N_m is the number of the magnets. $F_{tp}^{(1)}$ and $F_{tp}^{(2)}$ are tangential forces on the p th magnet within the inner and outer air-gaps, and $F_{rp}^{(1)}$ and $F_{rp}^{(2)}$ are the radial ones. The numbers of the outer and inner stators' slots are N_{s1} and N_{s2} , respectively, and the first tooth on the outer stator is located at the polar axis, and that on the inner stator is α , measured from the axis. Notations u and v represent the tangential and radial displacements, all related to position angle θ and time t . The radial width, axial length, density, Young's modulus, and the neutral circle radius of the rotor are W , L , ρ , E , and R .

2.2. Governing equations

This work is confined to the lower speed motors, and the equation of motion of the rotor can be readily developed. Since studies on ring structures can be widely found in the literature, such as the classical studies [34–36], this section briefly presents the derivation. According to Fig. 1, the kinetic energy can be written as

$$T = \frac{1}{2} \rho A R \int_0^{2\pi} \left[\left(\frac{\partial v}{\partial t} \right)^2 + \left(\frac{\partial u}{\partial t} \right)^2 \right] d\theta, \quad (1)$$

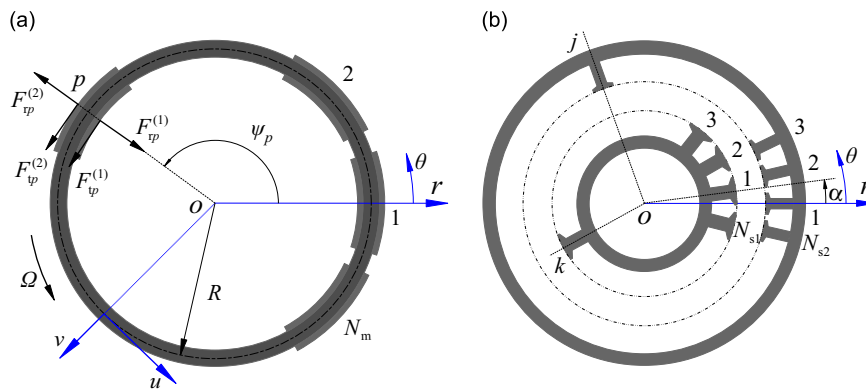


Fig. 1. Schematic of dual-stator PM motors and rotor-fixed coordinates.

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