Influence of Axial Asymmetrical Rotor In PMAC Motor Operation

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Abstract — To the permanent magnetic (PM) AC motor with the rotor aligned asymmetrically in axial direction, the motor magnetic field is axial-asymmetric. This asymmetric field generates unbalanced magnetic pull (UMP), and the analysis shows that, the UMP value varies in the motor operation. Analysis shows also that, if the number of stator slot is odd, the UMP center varies in the motor operation. The paper presents an analytical model for analyzing the effects of the UMP induced by the axial-asymmetrical rotor. The numerical results of PMAC motors are also presented, and they confirm the effectiveness of the analytical UMP model presented.

I. INTRODUCTION

For realizing some special characteristics, many PMAC motors have the rotor aligned asymmetrically in axial direction (Z-asymmetrical rotor). For example, many PMAC motors use Hall sensor to detect rotor position. To make the rotor magnetic field be detectable clearly, the rotor is aligned asymmetrically in axial direction, and this can make the sensors be close to the magnet; see Fig. 1. Another example is the spindle motor used in hard disk drive. For generating the preload to the bearing, the Z-asymmetrical rotor is also used; see Fig. 2. However, as the mechanical structure is axial asymmetrical, the magnetic field generated by the permanent magnet on the rotor acts with the stator core and generates an additional UMP in the motor operation.

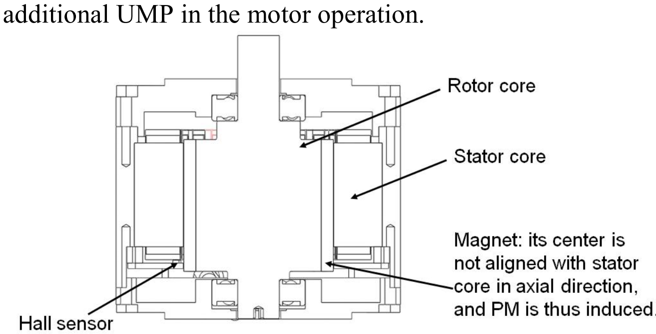

Fig. 1 The PMAC motor with the rotor aligned asymmetrically in axial direction

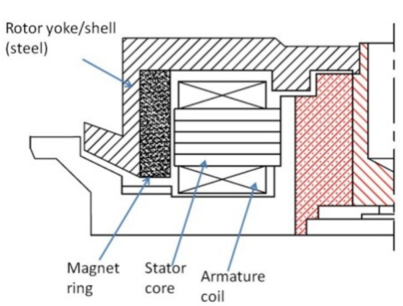

Fig. 2 The spindle motor with Z-asymmetrical rotor

II. UMP INDUCED BY ROTOR ALIGNED ASYMMETRICALLY IN AXIAL DIRECTION

For the PMSM with Z-asymmetrical rotor, the magnetic field generated by the permanent magnet trays to align the rotor magnetic center with the stator magnetic center, and an UMP is thus induced. Such an UMP may contain the components in different directions, but only its component in axial direction is considered in this paper, as it is clear, this is the dominant component of this kind of UMP.

There are many kinds of PMAC motors [3][4]. In this paper, the analysis concentrates on the motors with surface PM ring. This kind of motor is widely used in low power applications, e.g, the spindle motor used in hard disk drive, and the cooling fan motor used in PCs.

Fig. 3 and Fig. 4 show the simplified electromagnetic (EM) models of PMAC motor with Z-asymmetrical inner and outer rotors, separately. From the viewpoint of magnetic circuit analysis, there is no difference in the models for analyzing the PMSM with the inner and outer rotor. In this paper, for making the analysis be concise, only the PMSM with outer rotor will be used as example in the analysis.

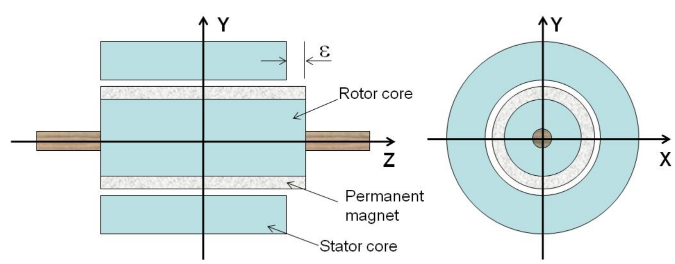

Fig. 3 A simplified model for describing the PMAC motor with Z-asymmetrical rotor (inner rotor)

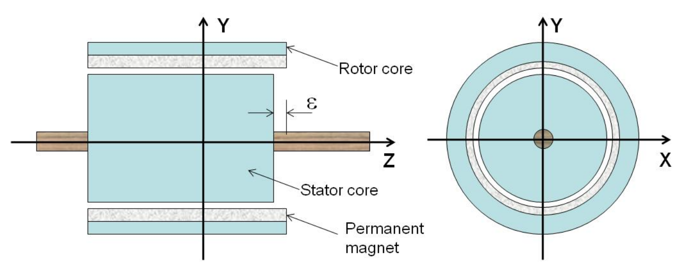

Fig. 4 A simplified model for describing the PMAC motor with Z-asymmetrical rotor (Outer rotor)

III. Influence of Stator Slots to The UMP Induced by Z-Asymmetrical Rotor

The magnetic field on the axial edge of the motor is related certainly with the permanent magnets on the rotor, and also the stator core structure, especial the slots on the core. If there is not slot on the stator, the geometrical relationship between the rotor and stator is fixed, i.e., from the viewpoint of rotor, the magnetic relationship between the rotor and stator is not affected by the rotor position. In this case, as the field generated by the armature winding currents in the axial edge is normally much weaker then the field generated by the magnet, the magnetic pull produced by the permanent magnet is constant. It also means, for the slotless PMAC motor, if the UMP in one rotor position can be known, the UMP on the other positions can also be known.

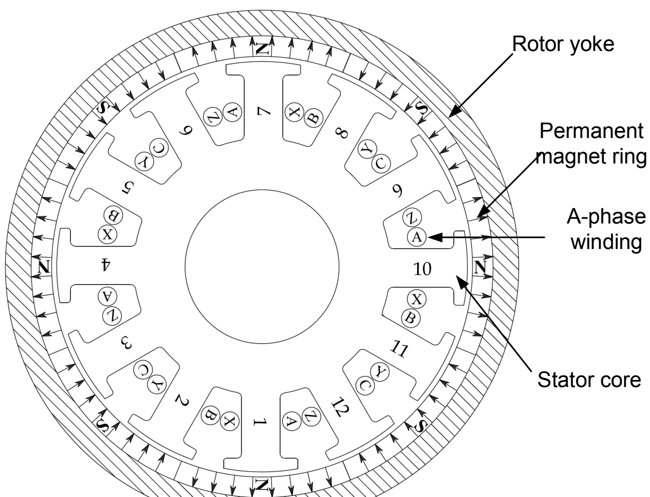

Fig. 5 A spindle motor with 12 slots and 4 magnetic pole-pairs (Motor-A)

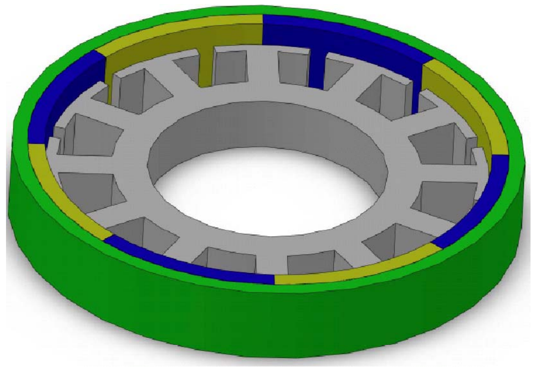

Fig. 6 The axial edgy of Motor-A

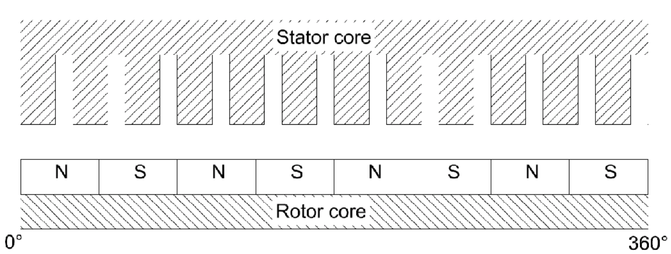

Fig. 7 A simplified model for describing the variation of the airgap of axial edgy of the spindle motor

However, the existence of the stator slots makes the geometrical relationship between the rotor and stator be complicated. The influence of the edgy magnetic field varies with the rotor rotation. This makes the UMP varies with the rotor rotation. One example is the motor shown in Fig. 5 and Fig. 6. It is a spindle motor with outer rotor. From the viewpoint of the magnetic circuit, the effective airgap of the motor axial edgy can be expressed with the simplified model shown in Fig. 7. From he viewpoint of the rotor, the length of the local airgap changes when the rotor is at different position.

IV. UMP Characteristic in The Space Domain

From Fig. 7, the effective permeance of the axial edgy airgap can be expressed as

$$\Lambda_A(\theta) = \Lambda_{A0}[1 + \sum_{n=0} \lambda_{An} \cdot Cos(nZ\theta)], \tag{1}$$

where, Λ_{A0} is the effective average permeance of the airgap, which is related with ε, the difference between the lengths of rotor and stator; see Fig. 3 and Fig. 4. Λ_{A0} is also linked with the thickness and permeability of the magnet, and the stator slot structure. Z is the number of stator slot. λ_{An}, is the coefficient of the nth order unit permeance of the airgap.

In the motor operation, the magnetic-motive-force (mmf) generated by the PM ring can be described by,

$$F_A(\theta,\alpha) = \sum_{n=0} K_{A,2n-1} Sin[(2n-1)p(\theta+\alpha)], \tag{2}$$

where, θ is the position of the field, p is the pole-pair of the PM ring, and α is rotor phase difference to the stator reference point. It is clear, α is a function of time and rotor speed.

Using magnetic-circuit method, the effective magnetic flux density in the airgap can be expressed as

$$B_A(\theta,\alpha) = \Lambda_A(\theta) \cdot F_A(\theta,\alpha). \tag{3}$$

The local radial force area density at position θ can thus be calculated by

$$p_A(\theta,\alpha) = \frac{\nu_0}{2} B_A^2(\theta,\alpha). \tag{4}$$

where, ν_0 is the reluctivity of vacuum.

Therefore, the UMP, $P_A(\alpha)$, can be calculated by using the following equation,

$$P_A(\alpha) = \varepsilon_A \int_0^{2\pi} p_A(\theta,\alpha) R_A d\theta = \frac{\nu_0 \varepsilon_A R_A}{2} \int_0^{2\pi} B_A^2(\theta,\alpha) d\theta = \frac{\nu_0 \varepsilon_A R_A}{2} \int_0^{2\pi} \Lambda_A^2(\theta) F_A^2(\theta,\alpha) d\theta, \tag{5}$$

where, ε_A is the effective length difference between the stator core and permanent magnet; see; see Fig. 3 and Fig. 4. R_A is the average radius of the airgap.

From (1) and (2) it can be known that,

$$\Lambda_A^2(\theta) = \sum_{m=0} l_{Am} \cdot Cos(mZ\theta)],$$

(6)

and

$$F_A^2(\theta,\alpha) = \sum_{n=0} f_{A2n} \cdot Cos[(2np(\theta-\alpha)]. \tag{7}$$

The definitions of l_{Am} and f_{An} can be found in [5].

Using the results shown in (6) and (7), the UMP can be expressed as,

$$P_A(\alpha)=\frac{v_0\varepsilon_A R_A}{2}\times \int_0^{2\pi}[\sum_{m=0} l_{Am}\cdot Cos(mZ\theta)][\sum_{n=0} f_{A2n}\cdot Cos[2np(\theta-\alpha)]]d\theta \quad . \quad (8)$$

From the orthogonality of the triangular function, it can be known that the integrations of all the items in (8) are zero except the items which can meet the following condition,

$$mZ = 2np\ . \quad (9)$$

Therefore, the following result can be obtained,

$$P_A(\alpha) = \frac{v_0\varepsilon_A R_A\pi}{2}\sum_{m=0}[l_{Am}[\sum_{n=0} f_{A2n}Cos(2np\alpha)]]\Big|_{mZ=2np} = P_{A0}+\frac{v_0\varepsilon_A R_A\pi}{2}\sum_q[l_{Aq}f_{Aq}Cos(q\alpha)] \quad , \quad (10)$$

where, P_{A0} is the zero order of the UMP, and q is the common multiple of Z and 2p.

Equation (10) shows clearly that, in the motor operation, the UMP induced by z-asymmetrical rotor is not a constant, and its frequency of fundamental harmonic in space domain is the minimum common multiple of Z and 2p. This result is very helpful in analyzing the vibration measurement results of PMAC motor. P_{A0} is normally the maximum component in the UMP, and its value can be predetermined by the lengths of rotor magnet and stator core, and the specifications of magnet material. The equation shows also that, selecting the reasonable matching between the numbers of stator slot and magnetic pole-pair of the motor can increase the order of the fundamental harmonic of UMP, and this can normally reduce the amplitude of UMP variation.

V. Variation of UMP Center In Motor Operation

If the location of the axial UMP center varies in the motor operation, even if its UMP is constant, the center variation can still induce acoustic noise and vibration, especially to the motors whose ratio of motor diameter to length is big, like the spindle motor used in hard disk drive.

As it was analyzed in Section-IV, in normally, the UMP is not constant in the motor operation. If the UMP center varies in the motor operation, the UMP influence becomes very complicated. It is necessary to investigate which factors affect the variation of the UMP center.

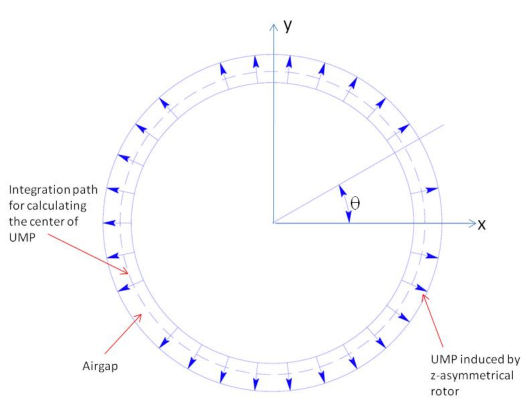

Fig. 8 Calculate the UMP center

When the distribution of the local z-asymmetrical axial force in tangential direction is known,

Fig. **8** can be used to express the way to calculate [X(α), Yα)], the location coordinate of the UMP center. The following equations can thus be obtained,

$$X(\alpha)=\frac{\varepsilon_A\int_0^{2\pi}p_A(\theta,\alpha)R_A Cos(\theta)d\theta}{P_A(\alpha)} = \frac{R_A\int_0^{2\pi}p_A(\theta,\alpha)Cos(\theta)d\theta}{\int_0^{2\pi}p_A(\theta,\alpha)d\theta} \quad , \quad (11)$$

and

$$Y(\alpha)=\frac{\varepsilon_A R_A\int_0^{2\pi}p_A(\theta,\alpha)R_A Sin(\theta)d\theta}{P_A(\alpha)} = \frac{R_A\int_0^{\pi}p_A(\theta,\alpha)Sin(\theta)d\theta}{\int_0^{\pi}p_A(\theta,\alpha)d\theta} \quad . \quad (12)$$

From (6) and (7), the integrations on the numerator of the right side of (11) and (12) can be written as

$$R_A\int_0^{2\pi}[\sum_{m=0} l_{Am}Cos(mZ\theta)][\sum_{n=0} f_{A2n}Cos[(2np(\theta-\alpha)]]Cos(\theta)d\theta\ , \quad (13)$$

and

$$R_A\int_0^{2\pi}[\sum_{m=0} l_{Am}Cos(mZ\theta)][\sum_{n=0} f_{A2n}Cos[(2np(\theta-\alpha)]]\mathrm{Sin}(\theta)d\theta\ . \quad (14)$$

If the stator slot is even, mZ is also even, and the functions to be integrated in above two equations can only form the odd triangular functions, and it is clear, the integrations for these triangular functions are zero. That is, if the stator slot is even, the following results can be obtained,

$$\begin{cases} X(\alpha)=0 \\ Y(\alpha)=0 \end{cases} . \quad (15)$$

Equations (15) means also, for the PMAC motor possessing even stator slot, its UMP center is always located at the center of the motor.

If the stator slot is odd, the integration of (13) and (14) can generate the following formats,

$$\sum_{n=1} U_n\cdot Cos(2np\alpha)\Big|_{2np=mZ+1}+\sum_{n=1} V_n\cdot Cos(2np\alpha)\Big|_{2np=mZ-1} \quad (16)$$

and

$$\sum_{n=1} U_n\cdot Sin(2np\alpha)\Big|_{2np=mZ+1}+\sum_{n=1} V_n\cdot Sin(2np\alpha)\Big|_{2np=mZ-1}\ , \quad (17)$$

where U_n and V_n are obtained by integrating (13) and (14), separately, and **m** is any of integers.

Equations (16) and (17) show that, when Z is odd, the fundamental orders of the numerators of (11) and (12) are the multiple number of the magnetic poles of the motor. In this case, as the denominators of (11) and (12) are formed by the even harmonics whose order is also the multiple of the magnetic poles, it can be concluded that the variation of the UMP center is formed by the even harmonics in both X and Y directions, and the order of the harmonic is the multiple of the motor magnetic poles.

VI. NUMERICAL ANALYSIS ON THE UMP

For verifying the analytical results obtained in the Section IV and V, several PMAC motors are calculated with 3D finite element method (FEM), and the FEM results are compared with the analytical ones. Here, the calculation results for two spindle motors are introduced, and they are named as Motor-A and Motor-B, separately. Motor-A has 12 stator slots and 4 magnetic pole-pairs, whose structure has been shown in Fig. 5 and Fig. 6. Motor-B is shown in Fig. 9. It has 3 stator slots and 2 magnetic pole-pairs. Both these two types of motor EM structure can be found in many applications.

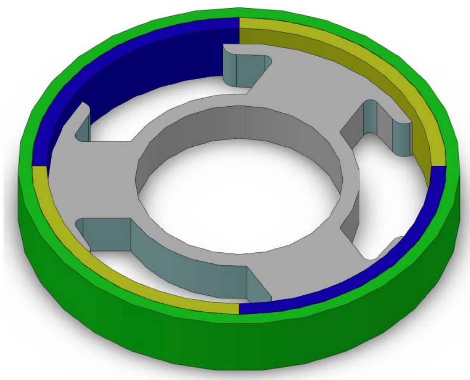

Fig. 9 A spindle motor with 3 slots and 3 magnetic pole-pairs (Motor-B)

Fig. 10 shows the flux lines of Motor-A obtained with 3D FEM. From the analytical analysis in the Section-IV, as Motor-A has 12 stator slots and 4 magnetic pole-pairs, its minimum common multiple of Z and 2p is 24. Therefore, the cycle width of fundamental harmonic of the UMP is 15°. This analytical deduction is confirmed by the UMP curve shown in Fig. 11, which is obtained from the 3D FEM results.

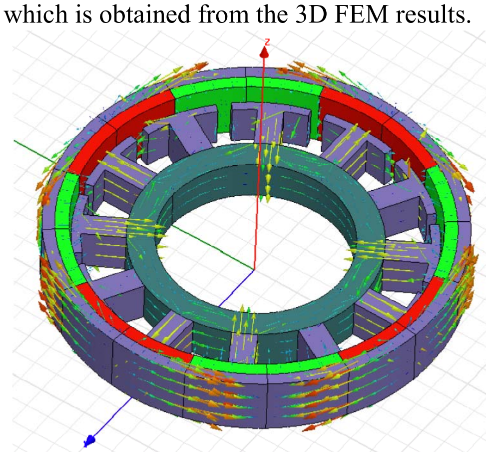

Fig. 10 The flux-lines of Motor-A

For checking the variation of the UMP center, FEM is also used for the center position calculation, and the results of Motor-A are shown in Fig. 12. As the motor has 12 slot and 4 magnetic pole-pairs, the rotor position range from 0° to 50° (mechanical degree) is enough for checking the variation cycle of its UMP. For this motor, the number of its stator slots is even, therefore, from the analytical analysis in the section-V, the center of UMP shouldn't change in the motor operation, and it should always locate at the center of the motor. It seems that the FEM results shown in Fig. 12 express the variation of the UMP center. As the average radius of Motor-A's airgap is 14.35 mm and the variation of the axial UMP center is less than 0.07 mm, the center variation shown in Fig. 12 can be considered as zero. It should be pointed out, the curves in the figure varies randomly; they are actually the numerical error which is ineluctable in using FEM. Using optimized FE mesh density and element shape can reduce such an error.

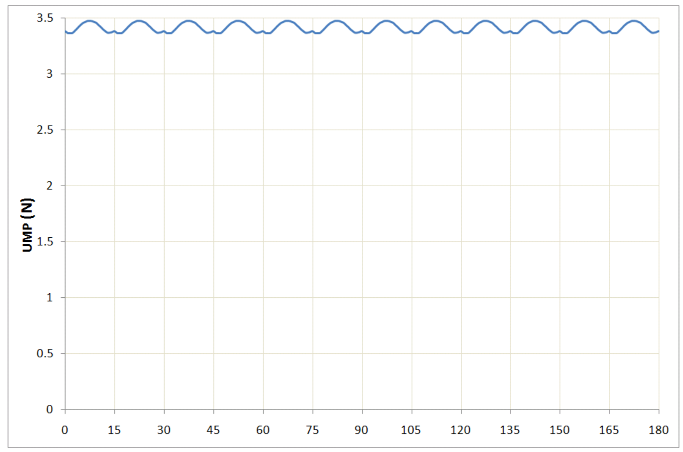

Fig. 11 The UMP value of Motor-A obtained with FEM

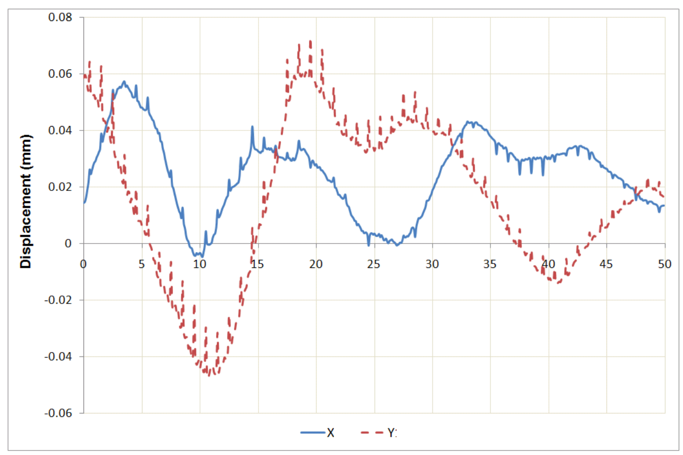

Fig. 12 The variation of UMP center of Motor-A obtained with FEM (Horizontal axial is the rotor position, and its unit is degree. x and y are the center components in x and y directions, separately)

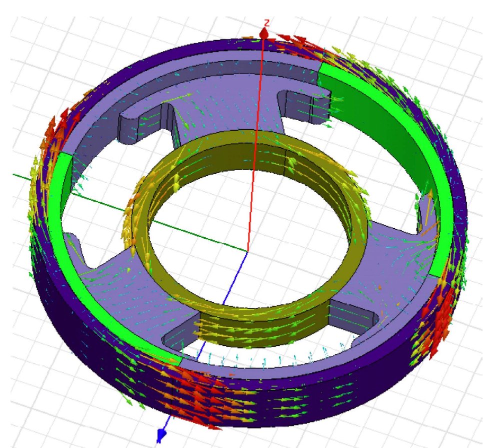

Fig. 13 The flux-lines of Motor-B

The FEM result of Motor-B's flux lines are shown Fig. 13, and motor's UMP is shown in Fig. 14. As the motor has 3 stator slots and 2 pole-pairs, the minimum common multiple of Z and 2p is 12. Therefore, the cycle width of UMP's fundamental harmonic is 30°, and this is confirmed by the UMP curve shown in Fig. 14, which is obtained with FEM.

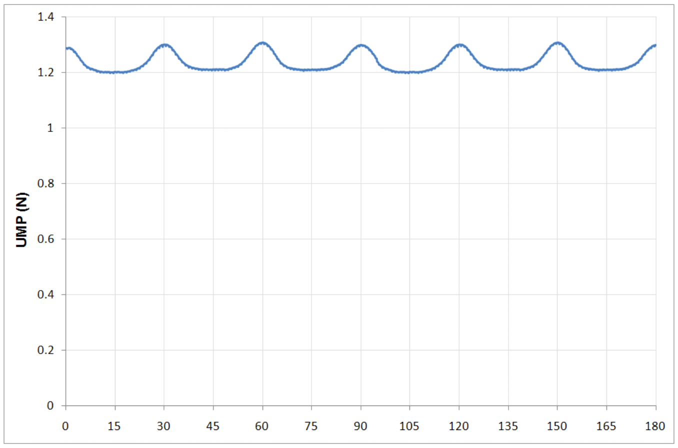

Fig. 14 The UMP value of Motor-B obtained with FEM (Horizontal axial is the rotor position, and its unit is degree)

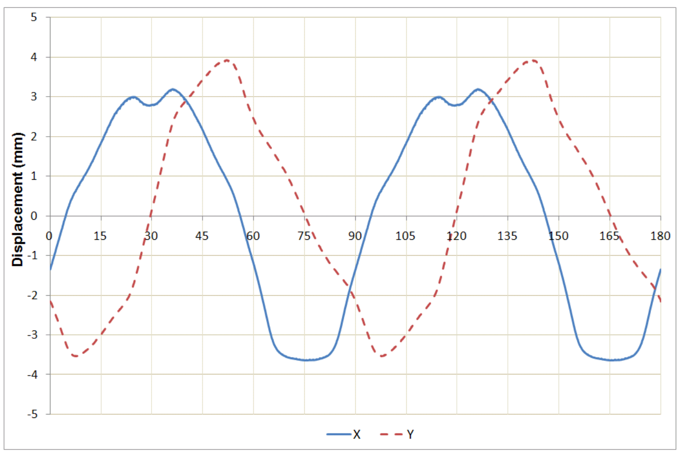

Fig. 15 The variation of UMP center of Motor-B obtained with FEM (Horizontal axial is the rotor position, and its unit is degree, x and y are the center components in x and y directions, separately)

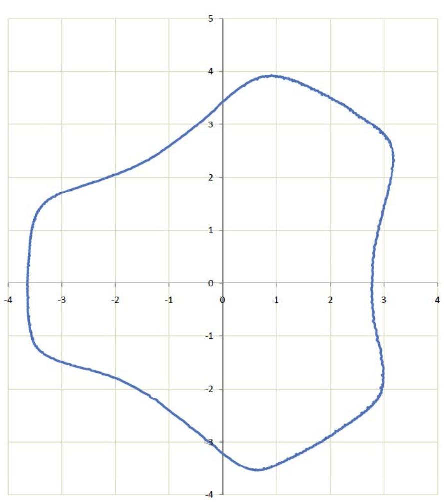
Fig. 16 The variation of UMP center of Motor-B obtained with FEM in Cartesian coordinate

The average radius of the Motor-B airgap is same as Motor-A, i.e., 14.35 mm. As its Z=3 and p=2, from the analysis in the Section-V, the location of the UMP center varies in the motor operation, and it is confirmed by the FEM results shown in Fig. 15 and Fig. 16. It is clear, as the variation is in a range whose maximum distance to the motor axis is 4.11mm, comparing with the radius of the motor airgap, the influence of such an UMP center variation is not neglectable in many applications.

From Fig. 15, it can be known that, the UMP center varies 4 times in one rotor revolution, and this fundamental order is just 2p, the magnetic pole-pair of Motor-B. This confirms also the analytical deduction to the UMP center variation in the Section-V.

From the calculation results of Motor-A and Motor-B, it can be known that, the axial UMP of Motor-A contains weak ripple than Motor-B. The reason of such a phenomenon is that, Motor-A has 12 slots and Motor-B has only 3. As increasing the slot number and magnetic pole-pair can make the minimum common multiple of slot and magnetic pole-pair be big, the order of UMP fundamental harmonic can thus be increased. This measure, in generally, can reduce the variation of the axial UMP.

VII. CONCLUSION

Though the UMP may induce serious vibration, acoustic noise and runout in the motor operation, the influences of the UMP generated by Z-asymmetrical aligned rotor have not been perceived well in many applications. The paper presents an analytical model to analyze this kind of UMP. The analysis shows clearly that, reasonable matching between the stator slot and magnetic pole-pair can reduce the UMP variation. Increasing the slot number and magnetic pole-pair of the motor can also reduce the variation. Using even stator slot can let the center of the UMP always located at the center of the motor. When the number of stator slot is odd, the variation of UMP center is formed by the harmonics whose order is the multiple of motor magnetic pole, and the variation of the center could be serious. These analytical deductions have been confirmed by the numerical results, and they can be used to analyze and realize high performance permanent magnetic AC motors, and can also be used in motor failure diagnosis.

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