An Iterative Magnetomechanical Deflection Model for a Magnetic Gear

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***Abstract*— This paper investigates the mechanical deflection within steel bars in a flux focusing magnetic gear. The deflection is caused by the magnetic attraction between the steel bars and the inner and outer rotor magnets. The non-linearity within the steel is considered.**

***Index Terms*—Magnetic forces, magnetic flux density, ferrite magnets, permanent magnets**

I. Introduction

A magnetic gear enables a contactless mechanism for speed amplification to be achieved. Magnetic gears do not require gear lubrication, they have inherent overload protection and they have the potential for high conversion efficiency [1-2]. A coaxial flux focusing magnetic gear (FFMG), as shown in Fig. 1, consists of p_1 pole-pair permanent magnets (PM) on an inner rotor rotating at ω_1, a middle rotor with n_2 ferromagnetic steel poles that can rotate at ω_2 and an outer stationary rotor (ω_3=0) with p_3 pole-pair PM. The PMs interact with the middle steel poles to create space harmonics [1-2]. If the relationship between the steel poles is chosen to be $p_1=|p_3-n_2|$ then the rotors will interact via a common space harmonic [2] and the angular velocities between the rotors will be

$$\omega_1 = \frac{n_2}{n_2 - p_3}\omega_2 \tag{1}$$

The parameters used by the FFMG are shown in Table 1. For p_1=4, n_2=17 and p_3=13 the gear ratio is 1:4.25. The predicted torque and torque ripple for this FFMG when using ferrite magnets (Hitachi NMF-12F, B_r=0.46T) and an axial length of 3inches is shown in Fig. 2. The low speed (cage rotor) bars are made of solid 416 stainless steel and are held in place on either end using end plates. This is shown in Fig. 3.

II. Magnetomechanical Displacement Analysis

In most electrical machines the elastic deformation due to magnetic forces is negligibly small [3] however it does play a role in creating vibration and acoustic noise [4-5]. In contrast, the FFMG cage bars are relatively thin and long and therefore the radial magnetic attraction force between the steel cage bars and inner and outer rotor magnets can create significant radial bar deflection. As the torque is highly dependent on air-gap an understanding of the level of deflection for axial bar lengths is of great interest.

The deflection of the cage bars will close the air-gap between the magnetic rotor and the steel bars leading to an increase in the magnetic force and consequently further deflection. Therefore, the magnetic force and bar deflection is highly coupled and the deflection varies along the axial length of the cage bars. The magnetic forces were first calculated using JMAG 3-D nonlinear finite element analysis (FEA) using a constant uniform air-gap along the axial length. The computed radial and tangential forces

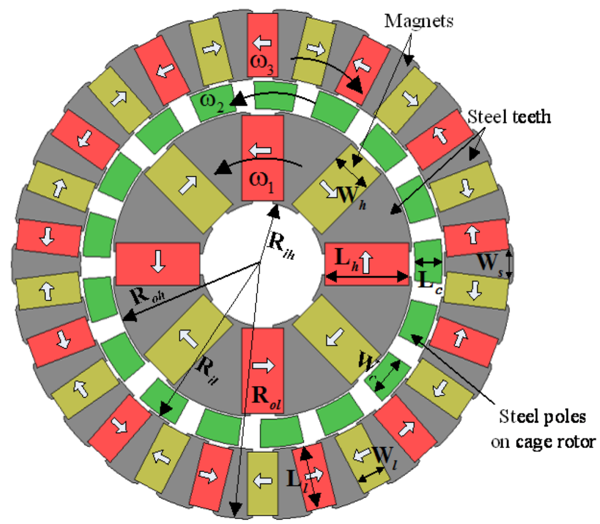

Fig. 1. 2-D model of a flux focusing magnetic gear with a p_1=4 pole-pairs, n_2=17 steel poles and p_3=13 pole-pairs on outer cylinder. 1:4.25 gear ratio.

TABLE 1
PARAMETERS FOR FLUX FOCUSING MAGNETIC GEAR

Cage rotor	Radial thickness of steel poles, L_c	6 mm
	Width of steel poles, W_c	14 mm
	Steel poles, n_2	17
	Air gap between each side of rotor	0.5 mm
Outer cylinder	Radial thickness of magnets, L_l	14 mm
	Width of magnets, W_l	7 mm
	Inner radius , R_{il}	40 mm
	Outer radius, R_{ol}	55 mm
	Pole pairs, p_3	13
Inner rotor	Outer radius of rotor, R_{oh}	33 mm
	Inner radius of rotor, R_{ih}	13 mm
	Magnet radial thickness, L_h	0.75 in
	Magnet width, W_h	3/8 in
	Pole pairs, p_1	4

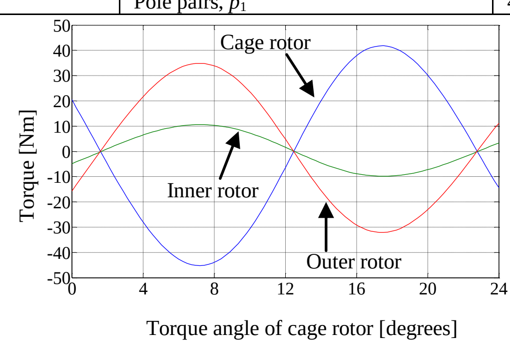

Fig. 2. Predicted torque as a function of relative angular position when only one rotor is rotating.

along the axial length on each FEA element were then used by a JMAG 3-D mechanical FEA package to compute the resulting deflection values when the ends of the bars were held fixed. The new deflected bar position along the axial length was then again used to compute magnetic force on the cage bars and so on. This iterative process was continued until no further significant deflection of the bars was observed. Fig. 4 summarizes the iterative approach.

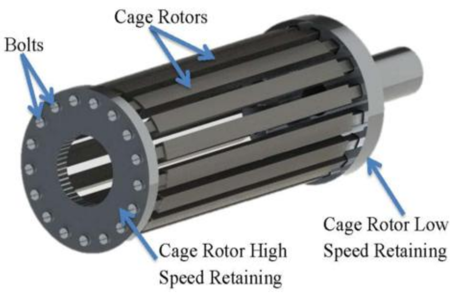

Fig. 3. Low speed rotor support

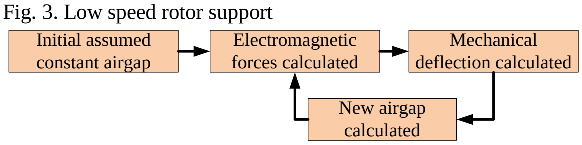

Fig. 4. Iterative magnetomechanical deflection analysis technique

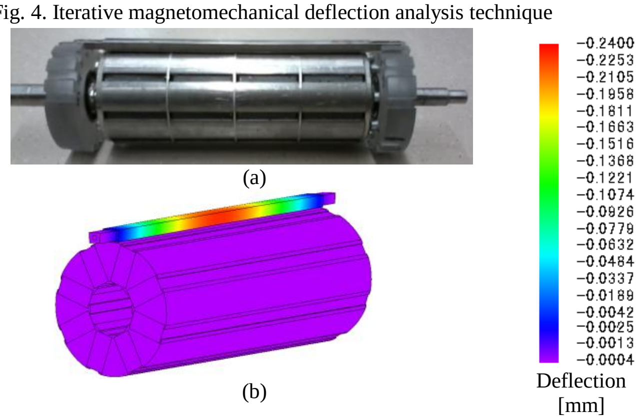

Fig. 5. Deflection analysis of single cage rotor bar due to the inner rotor flux focusing rotor (a) Experimental model, (b) FEA magnetomechanical analysis results when the initial airgap is 0.77 mm.

III. Verification And Analysis

In order to validate the iterative deflection analysis approach an experimental model, shown in Fig. 5(a), involving a single bar and flux focusing inner rotor was used. The deflection on this bar was modeled using the 3-D model shown in Fig. 5(b). The calculated deflection as a function of iteration is shown in Fig. 6, the initial air-gap was 0.77mm. Fig. **7** shows the measured and calculated air-gap reduction due to the deflection. Very close agreement was obtained.

Using this iterative deflection analysis approach a full FFMG iterative deflection design analysis was conducted for a 3 inch and 6 inch axial length FFMG. The initial airgap was set to 0.5mm. The radial deflection results (reduction in air-gap) for both models are shown in Fig. 8. It can be noted that the peak deflection for the 6inch design is 0.36mm while the maximum deflection for 3inches is only 0.018mm. This result indicates that the deflection of the bars in a magnetic gear must be carefully designed in order to mitigate bending.

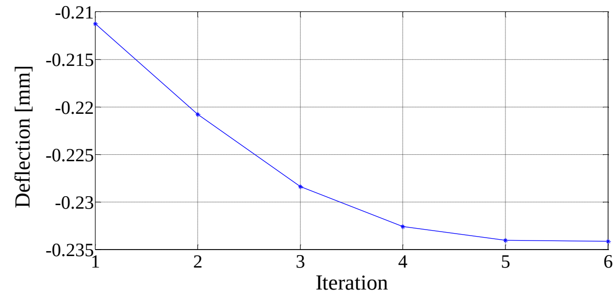

Fig. 6. Net deflection amount as a function of FEA iteration at axial position z=3.5inches for a single cage rotor bar. The deflection results show the deflection amount from an initial air-gap of 0.77mm.

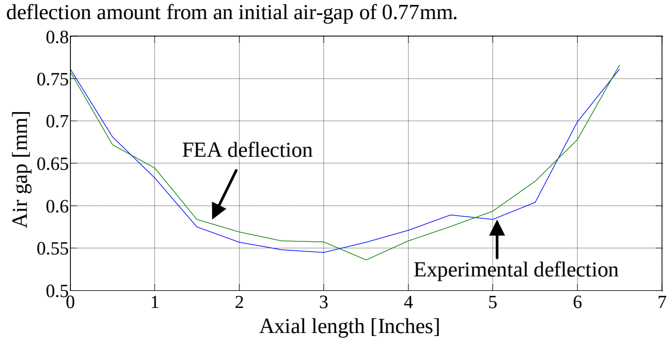

Fig. 7. Air-gap reduction of a single cage rotor bar along its axial length due to the inner rotor magnetic force.

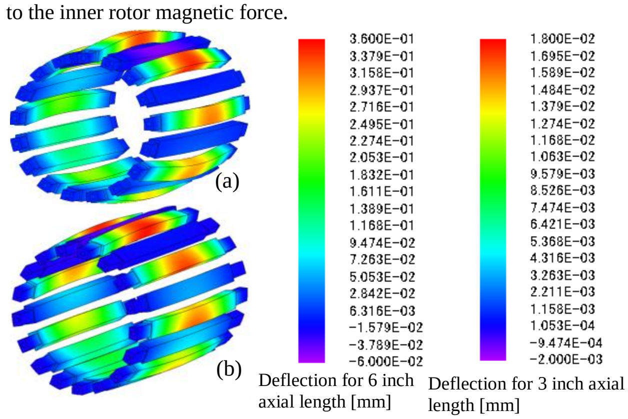

Fig. 8. Radial deflection of low speed (cage rotor) bars for an axial length of (a) 6 inches and (b) 3inches.

Conclusion

An iterative 3-D nonlinear magnetomechanical FEA technique has been applied to study the deflection of a FFMG. The modeling approach was validated using an experimental comparison.

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