Novel Heteropolar Hybrid Radial Magnetic Bearing with Double-Layer Stator for Flywheel Energy Storage System

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Background

Traditional heteropolar radial hybrid magnetic bearing (HRHMB) with eight poles has been widely applied in high-speed applications, such as flywheel energy storage system (FESS), because of its simple structure, low power loss, and high critical speed. However, this topology suffers large displacement stiffness, magnetic coupling, and non-negligible rotor iron loss. To overcome these drawbacks, one novel HRHMB with double-layer stator is proposed in this paper.

Objectives

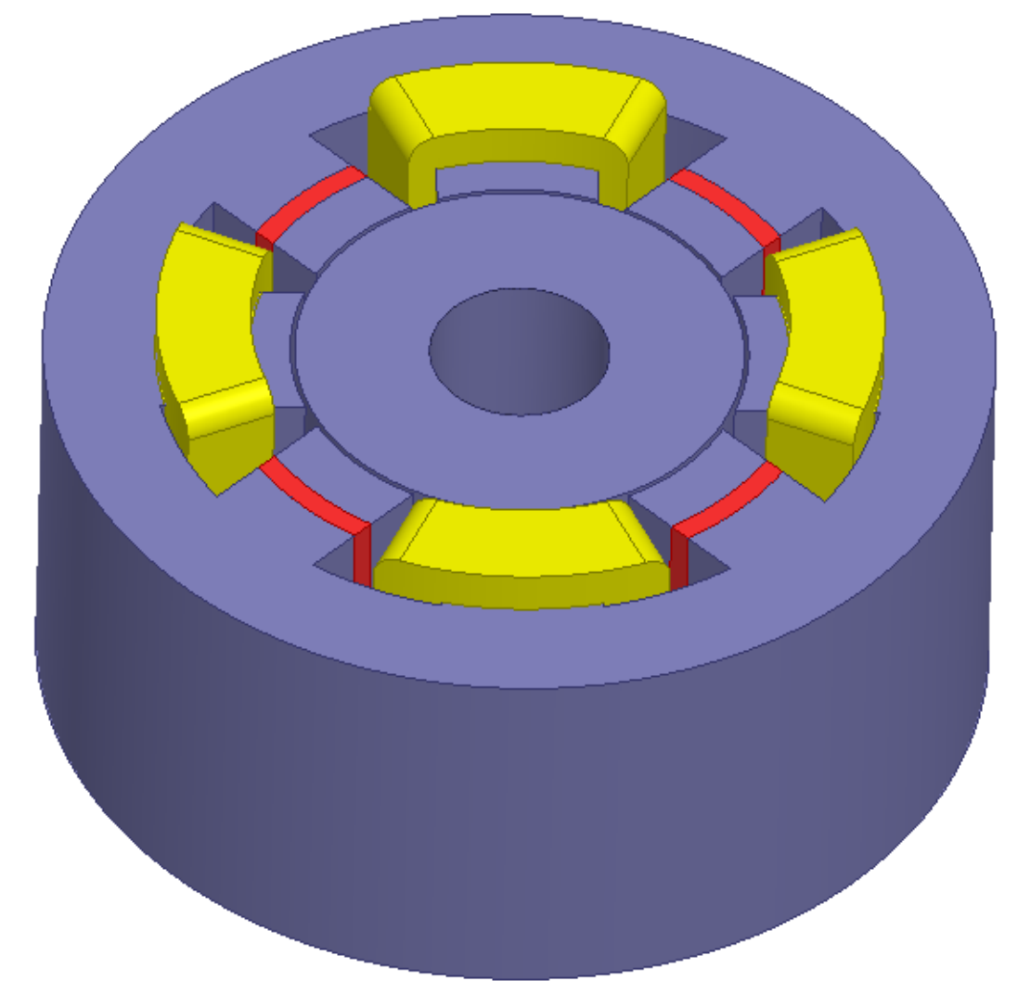
- The control of X and Y dimension in the new structure are independent of each other due to the effect of permanent magnet ring.
- Performance analysis of proposed HRHMB and the comparison with the conventional one from several key indexes, including displacement stiffness, current stiffness, magnetic coupling and power losses, *etc*.

Conclusion

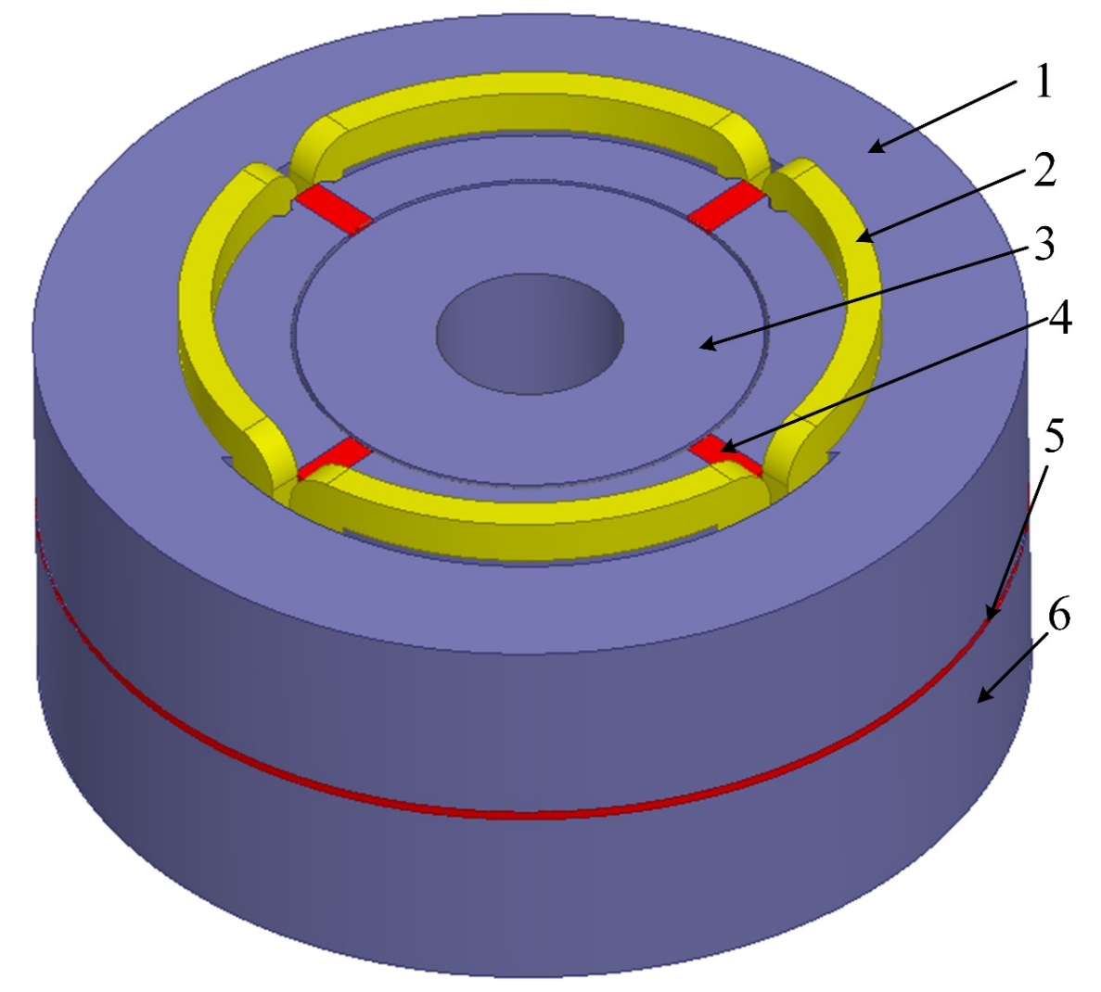
- One novel HRHMB is proposed and fully analyzed by 3-D FEM.
- The mathematical expressions are derived based on equivalent magnetic circuit model, including displacement stiffness, current stiffness and load capacity.
- Under the constraints of same outer diameter and load capacity, some key performance indices of new HRHMB are compared with those of conventional HRHMB in details .
- According to the results of comparison, it can be obtained that the displacement stiffness for novel HRHMB can be reduced to 64% from that (k_d=1.36 N/μm) of the conventional HRHMB. In addition, its current stiffness can be increased to 121.9% from that (k_i=179.2 N/A) of the conventional HRHMB.
- Moreover, the rotor core loss of the novel HRHMB can be decreased to 26.8% without load and 40.6% with maximum suspension force from those of the conventional HRHMB at rated speed 20,000 rpm..

Topologies

Conventional HRHMB

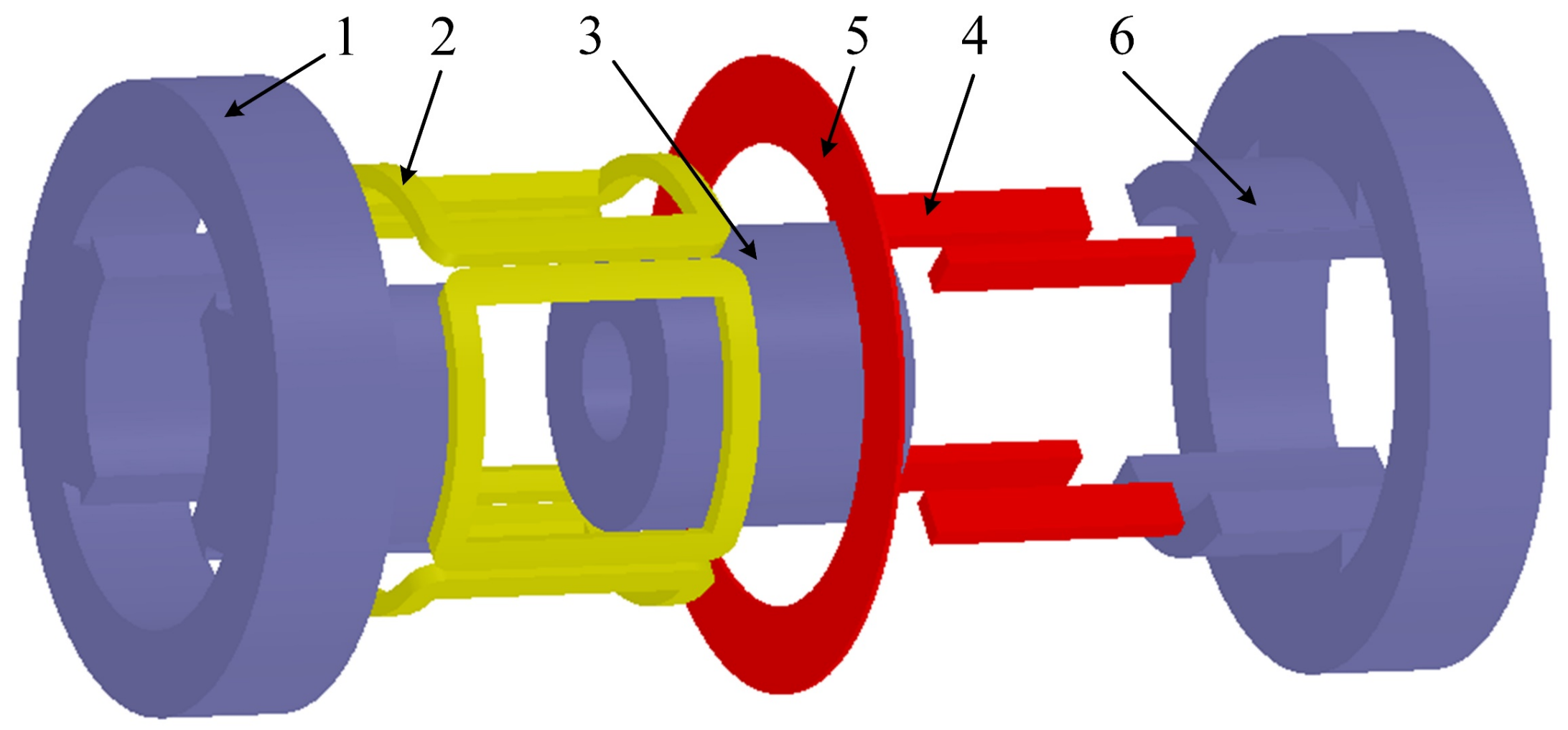


Novel HRHMB



In the novel structure, permanent magnets (PMs) are located between X and Y stator teeth, and X and Y stators are separated by PMs and PM ring. The bias-flux is closed through PMs, X and Y stator teeth, air gap and rotor and the control-flux is closed through X/Y stator, air gap and rotor respectively.

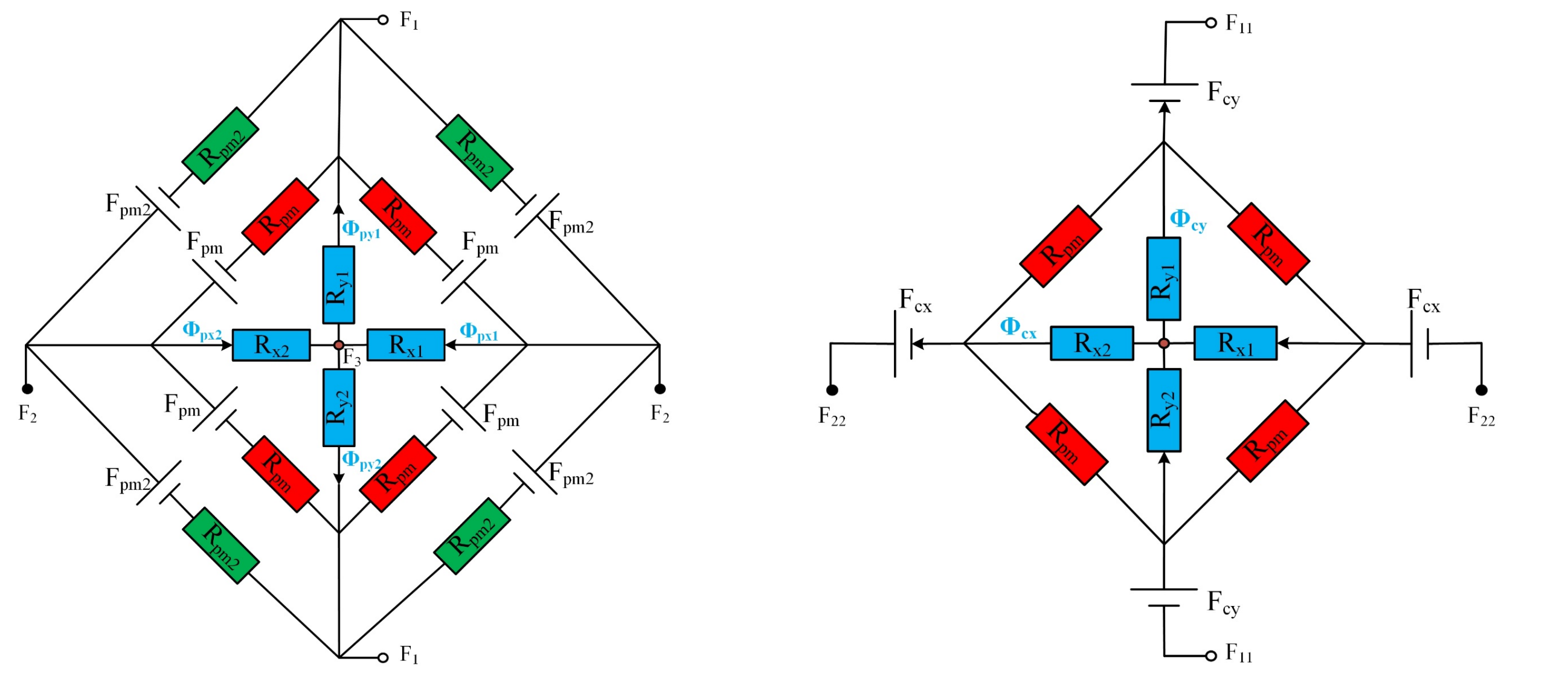
Exploded view of the novel HRHMB



Components: 1-upper stator (X stator), 2-control coil, 3-rotor, 4-permanent magnet, 5-permanent magnet ring, 6-lower stator (Y stator).
From this figure, it is known that stator includes four poles along the stator circumference, which forms heteropolar configuration with NSNS.

Model and Parameter

Flux paths of the novel HRHMB



Displacement stiffness:

$$k_d = -k_s \frac{8\left(F_{pm}R_{pm2} + F_{pm2}R_{pm}\right)^2}{\mu_0^2 A^2 R_0 [4R_0 R_{pm} + 4R_0 R_{pm2} + R_{pm}R_{pm2}]^2 \sigma_p^2}$$

Current stiffness:

$$k_i = k_s \frac{2\phi_{p0} N}{g\sigma_c}$$

Maximum load force:

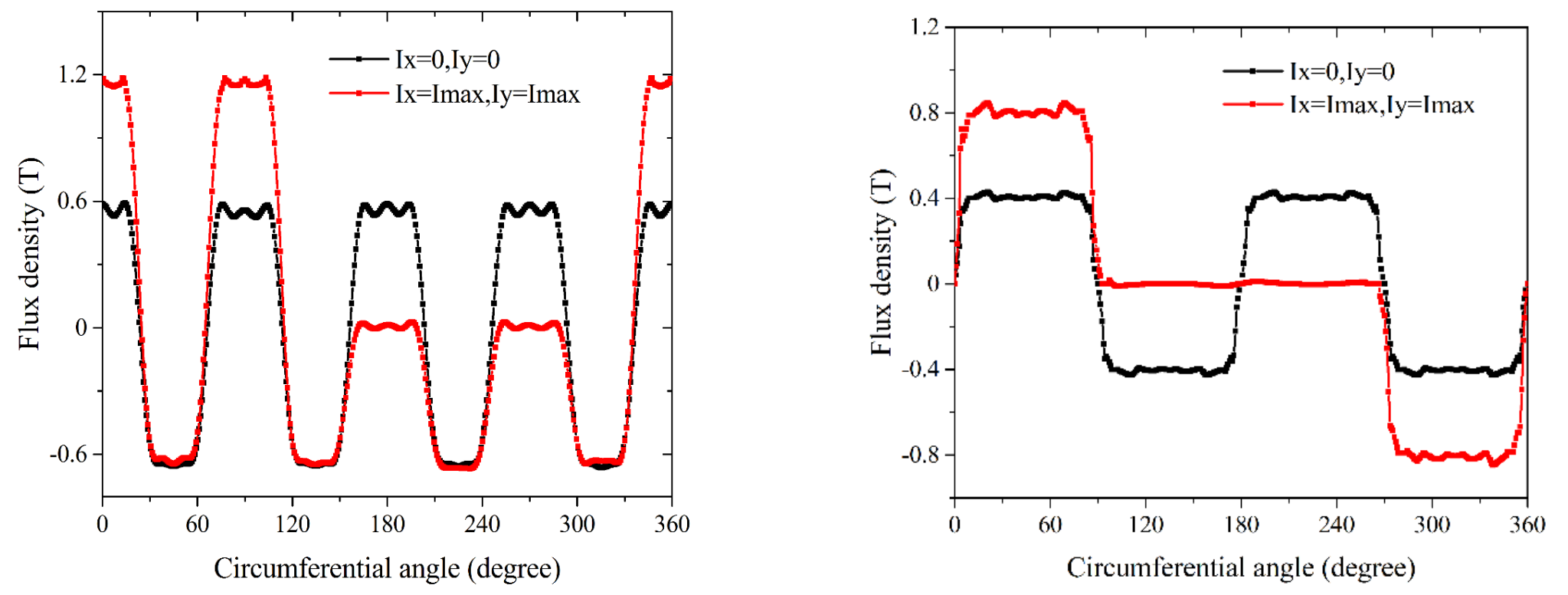
$$F_{\max} = k_s \frac{2\phi_{p0}^2}{\mu_0 A}$$

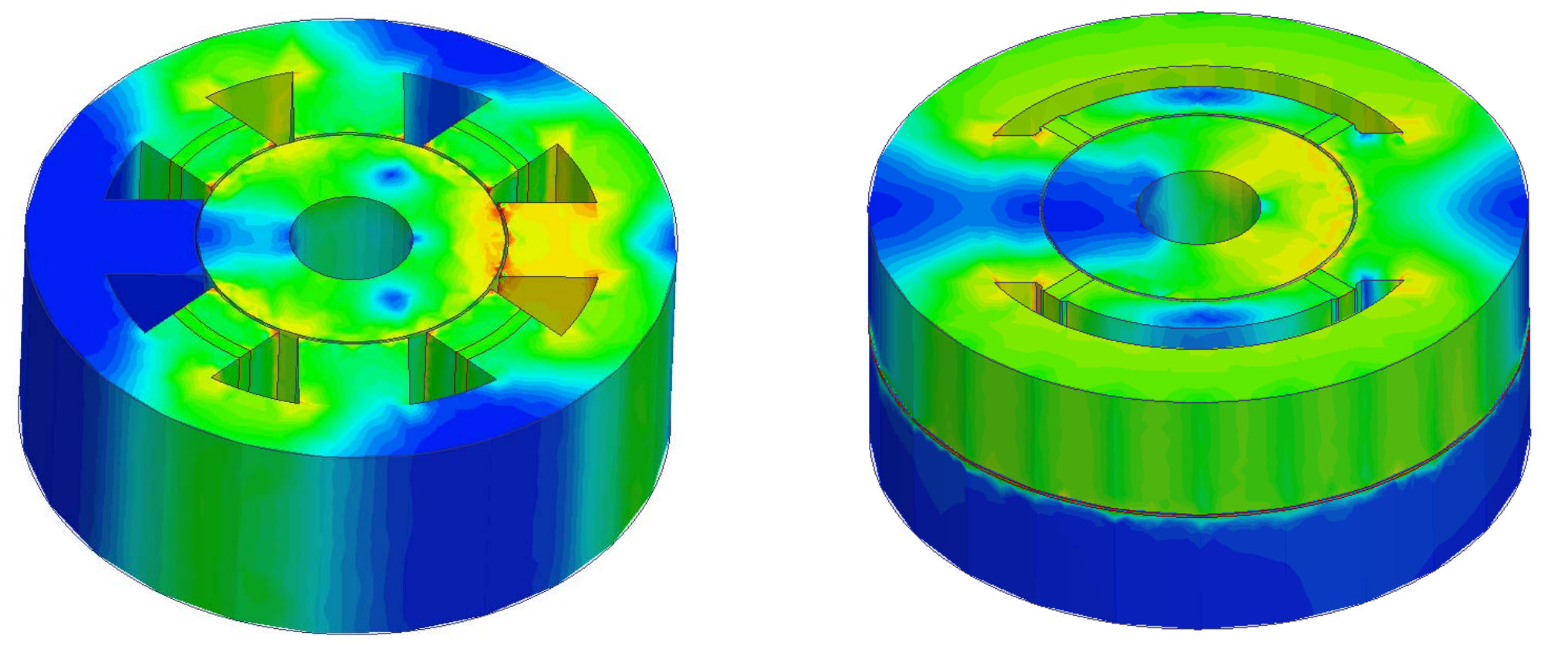
Main Specifications

Parameter	Value		Unit
	Conventional	Novel	
Outer diameter of the stator	106	106	mm
Outer diameter of the rotor	50	50	mm
Length of magnetic bearing	45	45	mm
Length of PM ring	-	0.5	mm
Length of air gap	0.5	0.5	mm
Thickness of PM	2.5	3.6	mm
Width of PM	15	8	mm
Area of magnetic pole	810	1600	mm^2
Turn of control coil	100	100	turn
Maximum control current	2.4	2	A
Bias flux density	0.6	0.4	T
Maximum load force	430	430	N
Rotor core material	50WW270	50WW270	-

Results

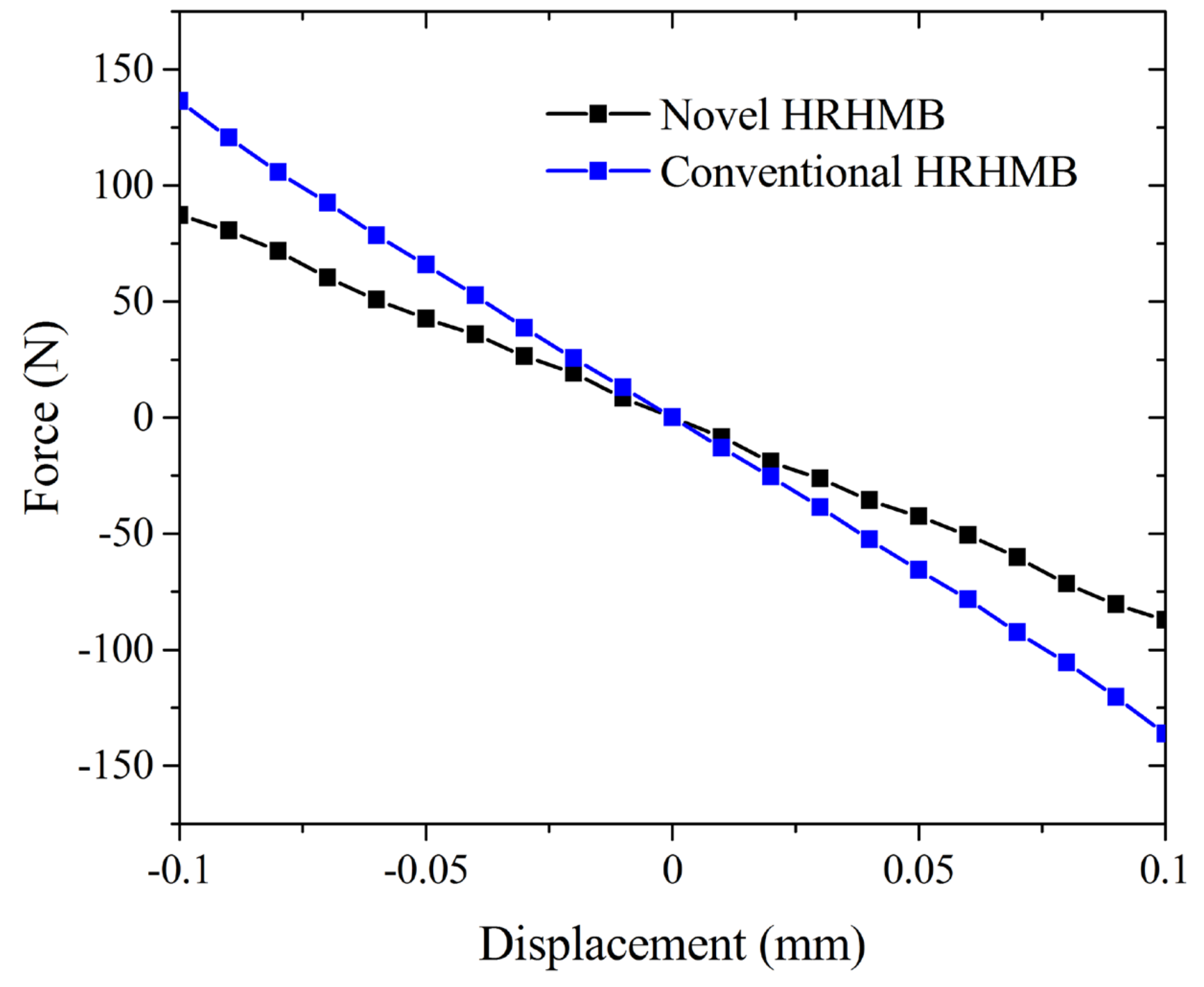
Magnetic field distribution



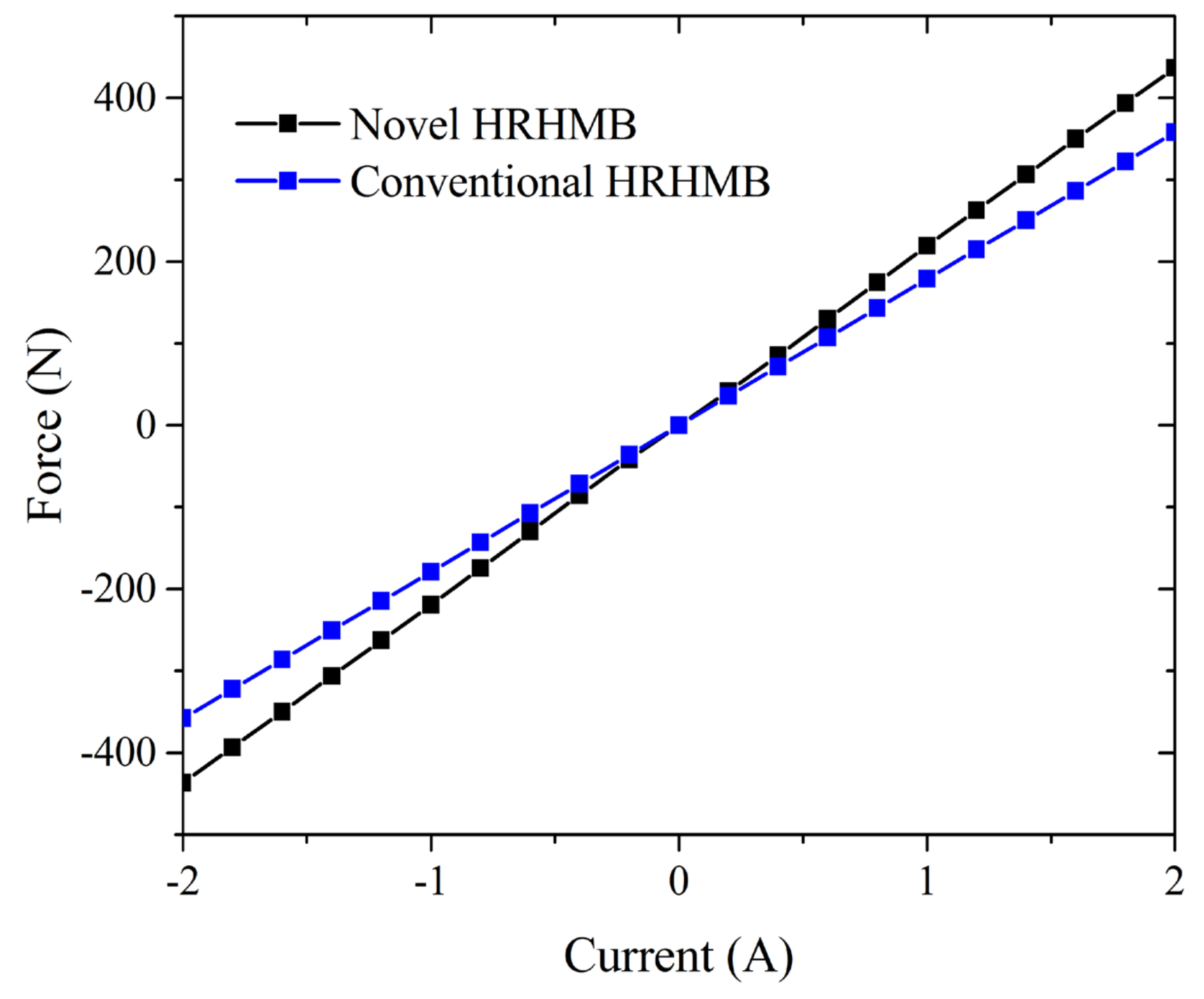


- Only four poles with active control coils, which means less fluctuation of magnetic field in the proposed novel HRHMB.
- The control of X and Y dimension are independent of each other in the new structure.

Displacement stiffness and Current stiffness



Force-displacement curves



Force-current curves

As shown in Figs, it can be observed that the displacement stiffness for novel HRHMB is smaller than that for conventional HRHMB, which indicates that the rotor for novel HRHMB returns central position more easily when it is offset. In addition, the current stiffness in the novel HRHMB is larger than that in the conventional HRHMB due to the larger magnetic pole region.

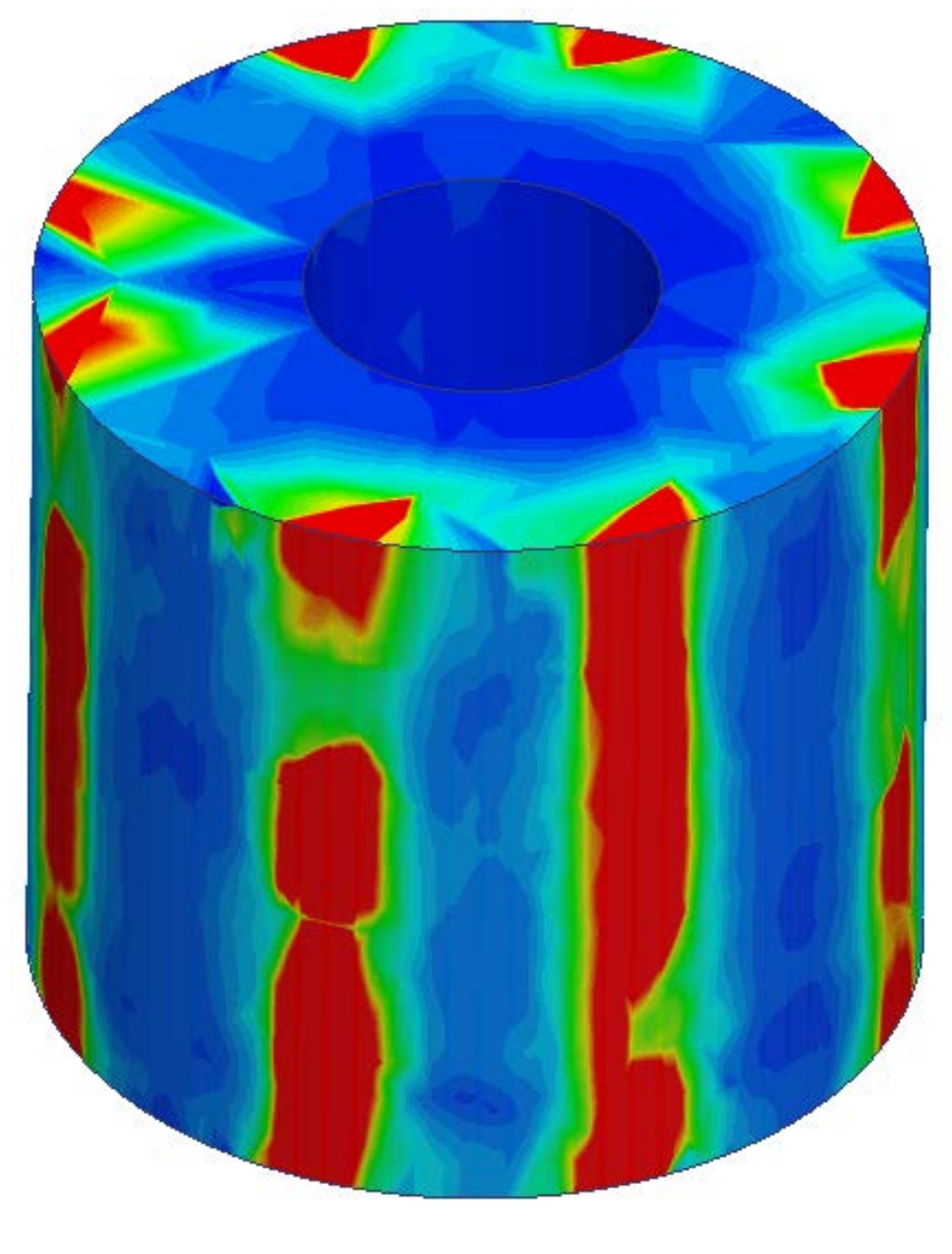
Magnetic coupling

To judge the magnetic coupling between the X- and Y-directions, a magnetic coupling coefficient (k_{xy}) is defined in this paper. It can be calculated by the maximum magnetic force in X- direction with different control currents in Y- direction.

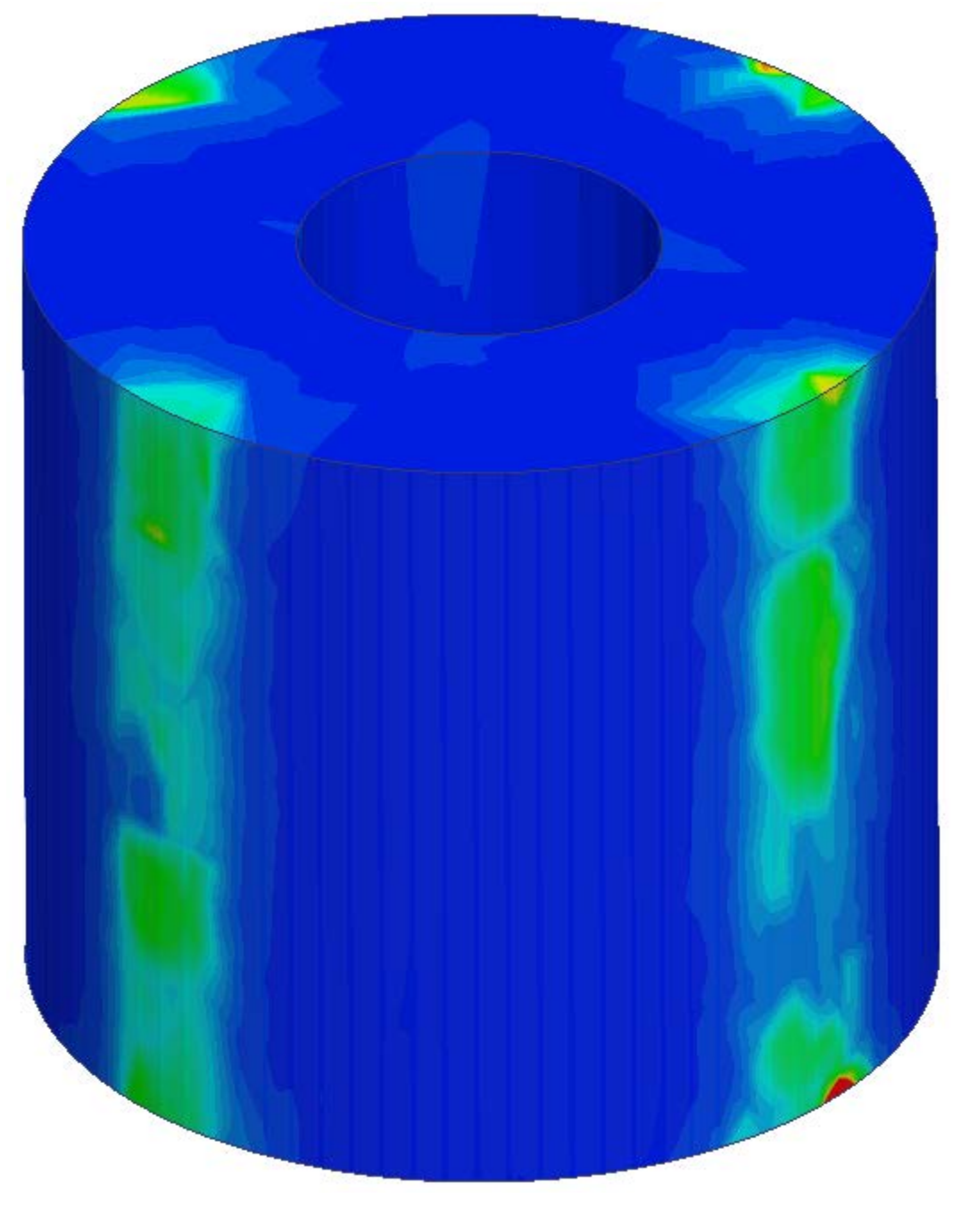
$$k_{xy} = \frac{F_x\big|_{i_y=0}^{i_x=i_{\max}} - F_x\big|_{i_y=i_{\max}}^{i_x=i_{\max}}}{F_x\big|_{i_y=0}^{i_x=i_{\max}}}$$

By calculating, the k_{xy} in conventional and novel HRHMB are 2.8% and 1.5%, respectively. It indicates that the x-axial magnetic force for the novel HRHMB decreases slower with the increasing of y-axial control currents compared with that for the conventional HRHMB, due to the double-layer stator structure.

Rotor core loss distribution



Conventional HRHMB



Novel HRHMB

Rotor core loss distribution with zero current at rated speed (20000 rpm) are shown in the Figs. It is observed that the rotor core loss is concentrated in the edge of the magnetic pole due to the fluctuation of magnetic field. The rotor core loss of the novel HRHMB can be decreased to 26.8% without load and 40.6% with maximum suspension force from those of the conventional HRHMB at rated speed 20,000 rpm.

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