Parameter Design of Six-pole Hybrid Magnetic Bearings Considering Variable Stiffness

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Background

Besides the advantages of the conventional magnetic bearings such as high speed and high precision, AC magnetic bearings also have advantages such as small size and low cost because of the use of mature technology of inverter driving. However, factors as non-uniform material, installation error, and non-uniform heating will cause the working point of the rotor to deviate from the given reference point, resulting in the change of the stiffness of the magnetic bearing in different positions, which will have a bad effect on the dynamic and static characteristics of magnetic bearing system. The parameter design of six-pole AC hybrid magnetic bearing (HMB) is carried out in the steady region determined by characteristics of variable stiffness coefficient.

Objectives

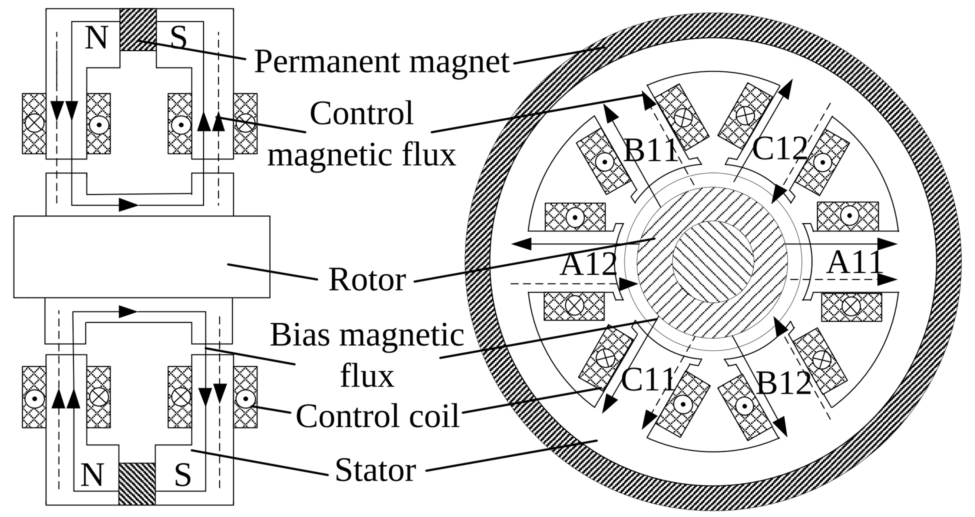
- ❖ Modeling
- ❖ Variable stiffness
- ❖ Parameter design
- ❖ Simulation

Working Principle and Mathematic Model of six-pole HMB

Working Principle

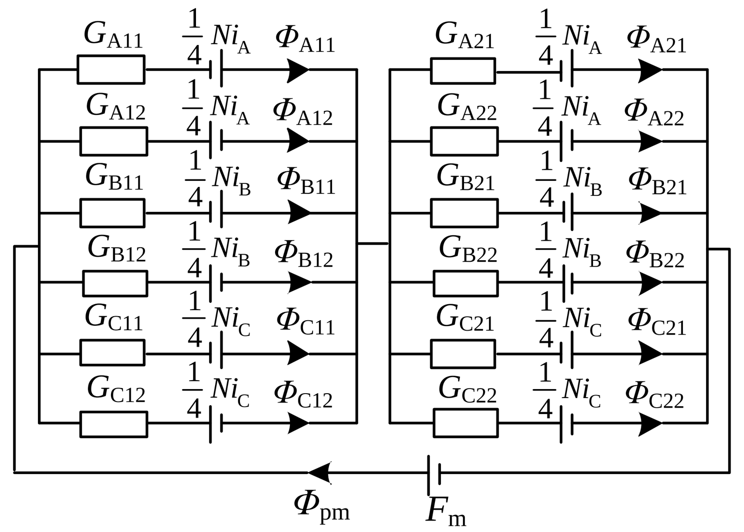
AC magnetic bearing is based on the principle of a bearingless motor. The torque winding pole-pair P_M is 0, and the suspension force winding pole-pair P_B is 1, when the condition of $P_B=P_M\pm1$ is satisfied, the radial suspension force of bearingless motor is produced.

The axial magnetized permanent magnet(PM) is installed between two radial stators, and the bias flux is Φ_{pm}, its flux loop is represented by solid lines with arrows. There are six protruding magnetic poles on each stator, and the control coils wounded on the magnetic poles are connected in series, and the control flux is Φ_{rm}, whose flux loop is represented by dash lines with arrows .



When the bearing is suspended stably, the rotor is in equilibrium position under the effect of PM bias flux. When the rotor deviates from the equilibrium position under the influence of external disturbance force, the bias flux on the small side of the air gap is larger, and the negative current is added into the control coil on the small side of the air gap, so the control flux is counteracted between the small side of the air gap and the bias flux, the suspension force of the small side of the air gap is reduced, and the rotor is subjected to the resultant force pointing to the large side of the air gap, thus returning to the equilibrium position.

Mathematic Model



Assuming that the rotor has only static working point eccentricity x_0 in x direction, when the rotor is offset in the radial direction, the suspension force of the six-pole AC HMB in the x direction is as follows

$$F_x = F_A - 0.5F_B - 0.5F_C = \mu_0 S_r\left[\left(\frac{2F_m+Ni_A}{4(\delta_r-(x+x_0))}\right)^2-\left(\frac{2F_m-Ni_A}{4(\delta_r+(x+x_0))}\right)^2\right]$$
$$-\frac{\mu_0 S_r}{2}\left\{\left[\frac{2F_m+Ni_B}{4\left(\delta_r+0.5(x+x_0)-\sqrt{3}y/2\right)}\right]^2-\left[\frac{2F_m-Ni_B}{4\left(\delta_r-0.5(x+x_0)+\sqrt{3}y/2\right)}\right]^2\right\}$$
$$-\frac{\mu_0 S_r}{2}\left\{\left[\frac{2F_m+Ni_C}{4\left(\delta_r+0.5(x+x_0)+\sqrt{3}y/2\right)}\right]^2-\left[\frac{2F_m-Ni_C}{4\left(\delta_r-0.5(x+x_0)-\sqrt{3}y/2\right)}\right]^2\right\}$$

Variable Stiffness Analysis of six-pole HMB

Static suspension force which considers the static working point in x direction can be expressed as

$$F_{x0}=\frac{\mu_0 S_r F_m^2}{4}\left(\frac{1}{(\delta_r-x_0)^2}-\frac{1}{(\delta_r+x_0)^2}+\frac{1}{(\delta_r-0.5x_0)^2}-\frac{1}{(\delta_r+0.5x_0)^2}\right)$$

The maximum suspension force of the rotor at the equilibrium position is as follows

$$F_{x\max}=\mu_0 S_r\left[\left(\frac{2F_m+0.5Ni_{\max}}{4(\delta_r-0.5x_0)}\right)^2-\left(\frac{2F_m-0.5Ni_{\max}}{4(\delta_r+0.5x_0)}\right)^2+\left(\frac{2F_m+Ni_{\max}}{4(\delta_r-x_0)}\right)^2-\left(\frac{2F_m-Ni_{\max}}{4(\delta_r+x_0)}\right)^2\right]$$

The maximum dynamic suspension force that six-pole AC HMB can provide in the actual working process is as follows

$$F_{dx}=\mu_0 S_r\left[\left(\frac{2F_m+0.5Ni_{\max}}{4(\delta_r-0.5x-0.5x_0)}\right)^2-\left(\frac{2F_m-0.5Ni_{\max}}{4(\delta_r+0.5x+0.5x_0)}\right)^2+\left(\frac{2F_m+Ni_{\max}}{4(\delta_r-x-x_0)}\right)^2-\left(\frac{2F_m-Ni_{\max}}{4(\delta_r+x+x_0)}\right)^2\right]-F_{x0}$$

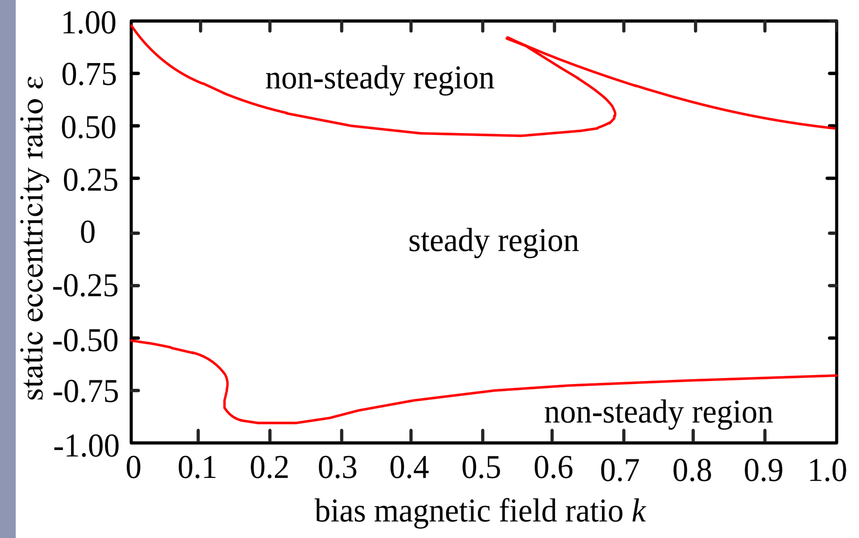
Define the dynamic stiffness k_{dx} of the six-pole AC HMB is as follow $k_{dx}=\frac{F_{dx}}{x}$

The displacement ratio γ is made to be the ratio of radial displacement x to air gap length δ_r. $\gamma=\frac{x}{\delta_r}$

The variable stiffness coefficient K is the ratio of dynamic stiffness k_{dx} to the average stiffness. Assuming $B_{max}=B_0+B_c$, B_0 represents the static bias magnetic induction intensity provided by the PM, Bc represents the magnetic induction intensity of the control magnetic field provided by the control coil, so the bias magnetic field ratio k is made to be the ratio of B_0 to B_{max}.

$$K=\frac{1}{\gamma}*\frac{F_{dx}}{F_{x\max}}=\frac{1}{\gamma}*\frac{a-b}{c}$$

$$a=\frac{(k+1)^2}{k^2(1-\gamma-\varepsilon)^2}-\frac{(3k-1)^2}{k^2(1+\gamma+\varepsilon)^2}-\frac{(2.5k-0.5)^2}{k^2(1+0.5\gamma+0.5\varepsilon)^2}+\frac{(1.5k+0.5)^2}{k^2(1-0.5\gamma-0.5\varepsilon)^2};$$
$$b=\frac{4}{(1-\varepsilon)^2}-\frac{4}{(1+\varepsilon)^2}+\frac{4}{(1-0.5\varepsilon)^2}-\frac{4}{(1+0.5\varepsilon)^2};$$
$$c=\frac{(k+1)^2}{k^2(1-\varepsilon)^2}-\frac{(3k-1)^2}{k^2(1+\varepsilon)^2}-\frac{(2.5k-0.5)^2}{k^2(1+0.5\varepsilon)^2}+\frac{(1.5k+0.5)^2}{k^2(1-0.5\varepsilon)^2}.$$



It can be seen that the variable stiffness coefficient K of the six-pole AC HMB is related to the static eccentricity ratio ε and the bias magnetic field ratio k.

Parameter Design of of six-pole HMB

➢ Parameter Design of Radial Stator Magnetic Pole Area and Control Coil Ampere-turns

$$F_{x\max}=\frac{3B_S^2 S_r}{2\mu_0}\qquad S_r=\frac{2\mu_0 F_{x\max}}{3B_S^2}\qquad Ni_{\max}=\frac{B_S S_r}{2\mu_0}$$

➢ Parameter Design of PM

$$F_{mb}=\frac{B_S S_r}{\mu_0}$$

➢ Parameter Design of Stator

$$W_H=D_H\sin\left(\frac{S_r}{L_H D_H}\right)\qquad D_{HRO}-D_{HRI}\geq W_H$$

Design requirements and known parameters of the six-pole HMB

Parameter	Value	Parameter	Value
Radial bearing capacity	100 N	Flux Density	0.8 T
Radial length of air gap	0.5 mm	Enameled wire diameter	0.67 mm

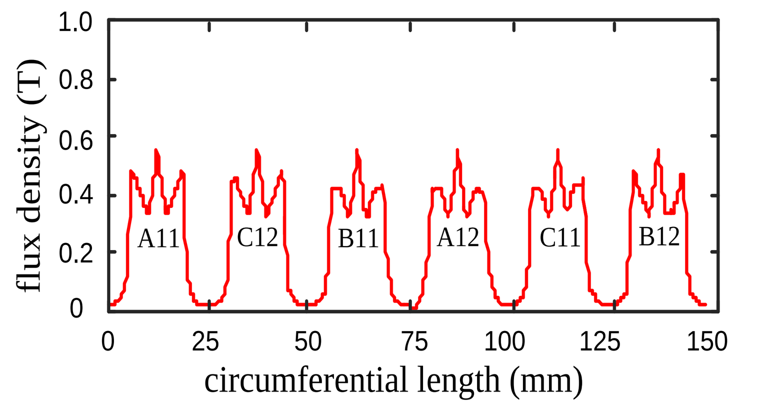
Parameter design results of the six-pole HMB

Parameter	Value	Parameter	Value
Inner diameter of rotor	24 mm	Thickness of PM	3 mm
Outer diameter of rotor	47 mm	Inner diameter of pole	48 mm
Inter diameter of stator	94 mm	Axial width of pole	12 mm
Outer diameter of stator	110 mm	Area of pole	150 mm²
Outer diameter of PM	100 mm	Magnetomotive force of PM	320 At
Outer diameter of PM	110 mm	Maximum ampere-turns per pole	160 At

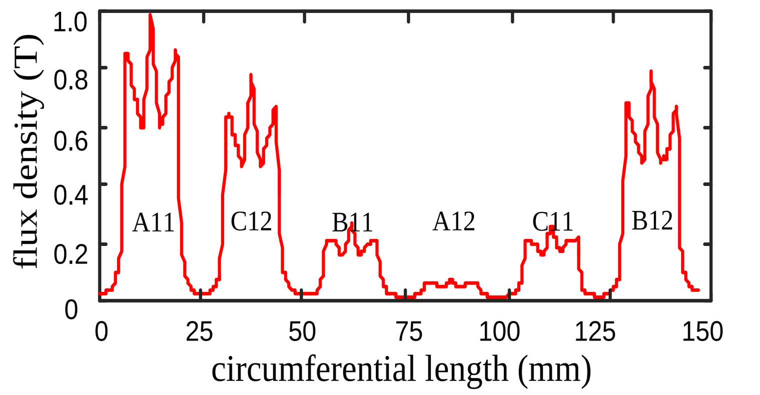
Conclusion

- ✓ The influence of the eccentricity of the rotor and the bias magnetic field ratio on the variable stiffness coefficient are analyzed, and the steady region of the six-pole HMB is pointed out, it provides a theoretical basis for the parameter design of six pole HMB.
- ✓ Simulation results show that the magnetic bearing system has well performance of anti-interference, and it is proved that the parameter design of the magnetic bearing is correct.

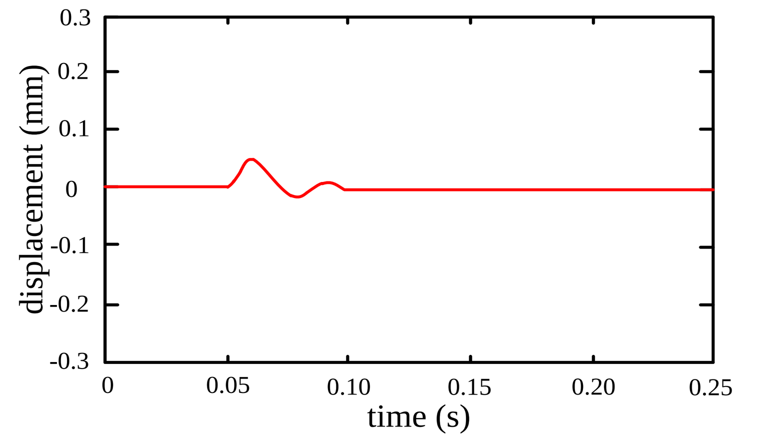
Simulation



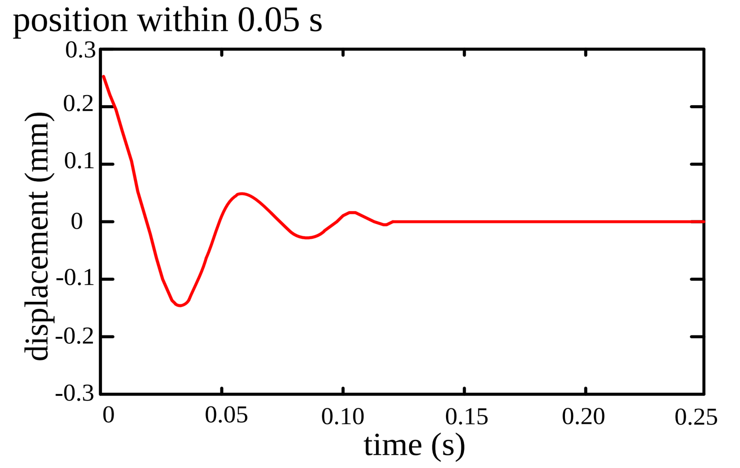
The magnetic flux density between the magnetic pole and rotor is about 0.4 T.



The maximum magnetic flux density between the each magnetic pole named A11 and rotor is about 0.8 T and the minimum magnetic flux density between the magnetic pole named A12 and rotor is about 0 T .



The external force is added to the rotor in x direction, the rotor returns to the equilibrium position within 0.05 s



The magnetic flux density between the rotor and the magnetic poles satisfy the design requirements. The initial position of rotor is assumed as (0.25 mm, 0) . Once the rotor is active, the rotor returns to the equilibrium position within 0.13 s.