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A design and analysis system of radial active magnetic bearings based on Comsol

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Abstract

The structrual design of active magnetic bearings (AMBs) is limited by multiple factors like installation space, performance of the soft magnetic materail and winding structures, etc. In industrial applications, complicated calculations are needed to obtain critical parameters of the AMB structure before establishing numerical models and finite element analysis to validate the design. The whole process could be iterative resulting in low effeciency in design. Based on Comsol, this paper describes the procedure of developing a system for radial AMB design and analysis. This system can perform parameter calculations based on several input parameters, after which a series actions of automated modeling and analysis are carried out. The system speeds up radial AMB design and evaluation, increasing the efficiency of engineering while decreasing the amount of work of engineers.

Keywords

Active magnetic bearing, desing, analysis, system development.

1. Introduction

The electromagnetic bearing uses electromagnetic force to provide the rotor supporting force, which can make the rotor run without contact and friction, so that the operating efficiency of the rotor is greatly improved [1-4]. Traditional rotor supports, such as rolling bearings, sliding bearings, air bearings, etc., mainly rely on mechanical force to support the rotor, while electromagnetic bearings use electromagnetic force to support the rotor. It is a typical mechatronic product involving rotor dynamics, mechanical structure, and electronics. Comprehensive application of technology and control theory in multiple disciplines. When designing electromagnetic bearings, especially radial electromagnetic bearings, various factors such as bearing installation space, bearing capacity, coil winding size, and soft magnetic material properties need to be considered, making the design process more complicated. In addition, after the parameter design is completed, if the electromagnetic field and electromagnetic force of the bearing need to be analyzed, a lot of simulation modeling and calculations need to be invested. If the parameters are to be optimized, multiple iterations of "design-simulation" may occur, resulting in a large workload and low design efficiency. For this reason, this paper develops a design analysis system based on Comsol to realize the parameter design and modeling and simulation of radial magnetic bearings. The system takes the bearing capacity as the goal and the radial space of the bearing as the constraint, which can better realize the parameter design of the radial electromagnetic bearing. After the parameters are selected, the geometry and simulation model of the electromagnetic bearing can be quickly constructed to realize the simulation of electromagnetic field distribution and bearing force.

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2. Working principle of radial electromagnetic bearing

The most basic working principle of electromagnetic bearings is to use electromagnetic attraction to act on the rotor to overcome the rotor's gravity, unbalanced force and other forces acting on the rotor to keep the rotor suspended and run stably. The working principle of general radial electromagnetic bearings is shown in Figure 1 [5]. The bearing stator and rotor are made of soft magnetic materials. When the coil windings on the stator are energized, there will be an electromagnetic field in the air gap between the stator and the rotor. This electromagnetic field generates a suction force between the rotor and the stator and provides the supporting force of the bearing. Since electromagnetic attraction is an unstable force, it is necessary to manually control the excitation current. To this end, a displacement sensor is provided in the bearing to detect the position of the rotor relative to the bearing. The position signal is sent to the controller for calculation, and the control current is adjusted according to a certain control algorithm. After being amplified by the power amplifier, it is sent to the stator winding. Therefore, the suspension rotor system supported by the electromagnetic bearing is always in dynamic balance. When an external excitation changes the rotor state, the system will respond to ensure the balance of the suspension rotor.

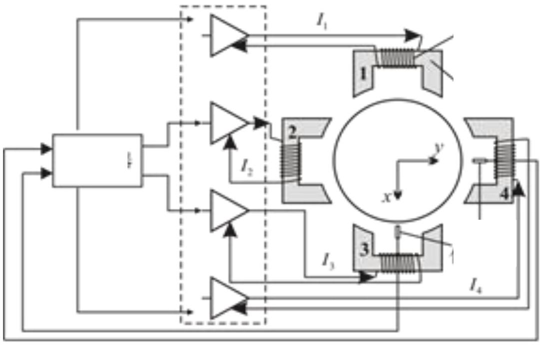

Figure 1 Principle of radial electromagnetic bearing system

The most commonly used radial electromagnetic bearing structures at this stage are C-type and E-type. The main structural differences between the two are shown in Figure 2. If differential control is used, the electromagnetic force generated in a certain direction (horizontal or vertical) is [6]

$$
\begin{aligned}
F_{\mathrm{C}} &= \frac{\mu_0 S_0 N^2 i_0^2}{4c_0^2}\cos\alpha\left[\left(\frac{i_0+i}{c_0+x}\right)^2-\left(\frac{i_0-i}{c_0-x}\right)^2\right]\\
F_{\mathrm{E}} &= \frac{9\mu_0 S_0 N^2 I_0^2}{32c_0^2}\left\{\cos\beta\left[\left(\frac{i_0+i}{c_0+x\cos\beta}\right)^2-\left(\frac{i_0-i}{c_0-x\cos\beta}\right)^2\right]+\left[\left(\frac{i_0+i}{c_0+x}\right)^2-\left(\frac{i_0-i}{c_0-x}\right)^2\right]\right\}
\end{aligned}
\tag{1}
$$

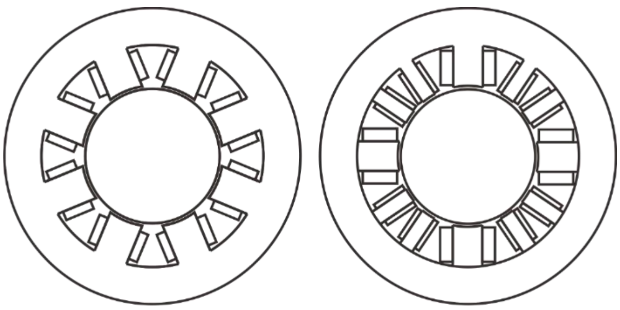

Figure 2 Type C and Type E radial magnetic bearings

Among them, μ_0 is the vacuum permeability, S_0 is the magnetic pole cross-sectional area, N is the number of coil turns, i_0 is the bias current, c_0 is the air gap between the stator and the

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rotor, i is the control current, and x is the displacement of the rotor in this direction. α is the angle between the magnetic poles in the C-type bearing, and β is the angle between the main magnetic pole and the secondary magnetic pole in the E-type bearing. These two parameters are related to the bearing geometry (number of magnetic poles, etc.). It can be seen that the electromagnetic force of the bearing is jointly determined by the geometrical structure parameters of the bearing and the current parameters.

Since the current parameters are mainly limited by the bearing power amplifier system [7], they are generally known parameters, so the most important thing when designing an electromagnetic bearing is to determine the key structural parameters of the bearing. In addition to the above geometric structure parameters, there are also the stator's inner and outer radius, width, magnetic pole width, height, enameled wire type, coil width and thickness, etc.

3. Calculation of electromagnetic bearing parameters

Before calculating the geometric parameters of the electromagnetic bearing, it is necessary to select the linear magnetic density range for the properties of the soft magnetic material. As any soft magnetic material is close to magnetic saturation, the BH curve will appear nonlinear, in order to facilitate control, often choose a linear segment (0~"B" _"max") in the material BH curve as the allowable magnetic Close the range, and take the working point "B" _"0" (usually "B" _"0" ="B" _"max" /2), as shown in Figure 3.

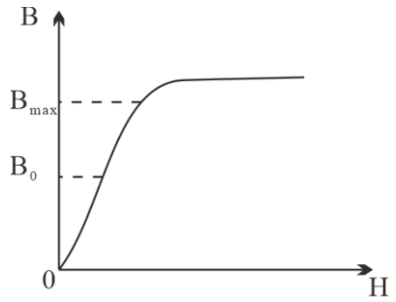

Figure 3 Selection of working point of magnetic flux density

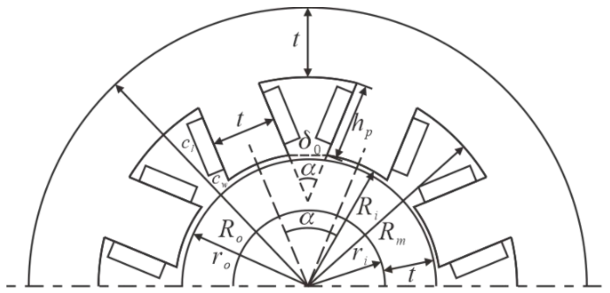

Figure 4 C-type radial electromagnetic bearing structure

After selecting "B" _"0", some electromagnetic bearing parameters can be calculated as follows (take C-type radial electromagnetic bearing as an example).

$$\begin{array}{ll} N=\frac{B_0 c_0}{\mu_0 i_0} & t=\frac{2\pi(r_o-h_p)-\delta_0 N_p}{2\pi+N_p} \\ d_c=\sqrt{\frac{4i_{max}}{\pi j_{max}}} & R_m=R_o-t \\ h_p=d_c\sqrt{\left(-\frac{2}{\pi}+\frac{1}{2k_c}\right)NN_p} & R_i=R_o-t-h_p \\ \delta_0=\frac{2Nd_c^2}{h_p} & L=\frac{F_{\max}\mu_0}{4tk_l B_0^2\cos(\pi/N_p)} \\ r_o=R_i-c_0 & r_i=r_o-t \end{array} \tag{2}$$

Where d_c is the bare wire diameter of the enameled wire, i_max is the maximum allowable current, j_max is the coil current density, h_p is the magnetic pole height, k_c is the coil slot full rate, N_p is the number of magnetic poles, δ_0 is the magnetic pole opening spacing, and t is the magnetic pole width (magnetic Yoke thickness), R_o, R_m, R_i are the outer radius, middle radius and inner radius of the stator, L is the stator width, k_l is the stacking factor of the stator laminations, r_o, r_i are the outer radius and inner radius of the rotor. Refer to Figure 4 for the clear meaning of each parameter. In this design system, r_o is an input parameter. Next, you need to determine the size of the coil winding, that is, the coil length c_l and the coil width c_w in Figure 4. Assuming that the coil is wound with N_l layers in the length direction and N_w layers in the width direction, then N_l N_w≥N. Assuming that each wire in the coil is wound side by side, then

$$\begin{cases} c_l = N_l(d_c + 2s) \\ c_w = N_w(d_c + 2s) \end{cases} \tag{3}$$

Where s is the thickness of the paint film. The requirements for the length and width of the coil are: the width direction must ensure that the coil can be installed in the wire slot, and the length cannot exceed the height of the magnetic pole. For this reason, you can choose to start the loop from N_l=1, add one to N_l each time, N_w=N/N_l, and at the same time determine whether the coil size meets the above two requirements, namely

$$\begin{cases} c_l < h_p \\ c_w < \delta_0 \end{cases} \tag{4}$$

If formula (4) is established, it means that the coil size is qualified and the coil design is completed.

4. Comsol implementation

The calculation process of the above-mentioned radial magnetic bearing geometric parameters can be automated with the help of Comsol's Application builder module and the use of java language. On the one hand, this module can use java language to realize complex algorithms, on the other hand, it can call Comsol software API to realize the automatic geometric model modeling, model setting, meshing, solving and result display that is output process controlled by the program. At the same time, the module also provides the implementation of Comsol-based program GUI, which can quickly build applications. The system interface described in this article is shown in Figure 5.

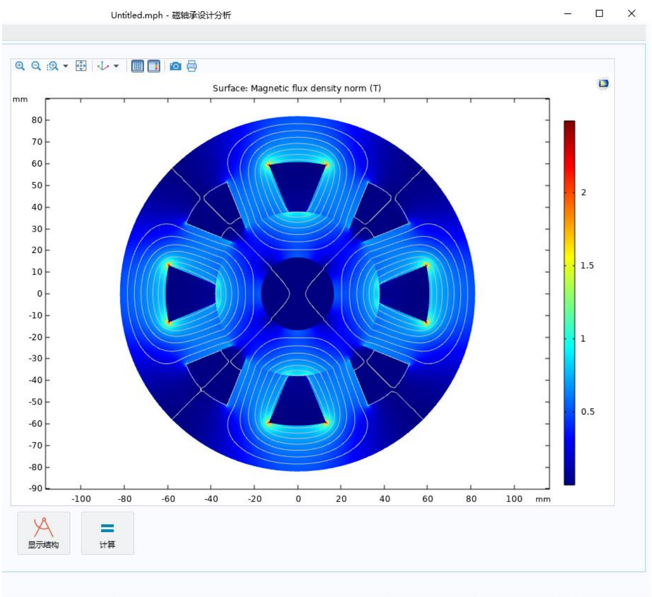

Figure 5 The interface of the electromagnetic bearing design analysis system

Model object

In Comsol, the Model object stores all the data related to analysis and calculation, and has a large number of methods (Methods), which can be realized including geometric modeling, meshing, model solving, and display results. It is the most basic object of Comsol.

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Geometry object

Geometry is a subset of Model objects, representing geometric models, and contains a variety of methods for generating geometric models. For example, if there is a Geometry object named geom1 in the model, a square with a side length of 0.9 and a name of sq should be created at the position of [0.5, 0.5]. The relevant code is

```
model.geom("geom1").create("sq", "Square");
with(model.geom("geom1").feature("sq"));
set("pos", new String[]{"0.5", "0.5"});
set("size", "0.9");
endwith();
```

In the system described in this article, using various methods of Geometry, the geometric model of the electromagnetic bearing can be established based on the calculated parameters.

Physics object

The Physics object contains all the attributes of the simulation object. For the system described in this article, since the electromagnetic module of Comsol is used, the Physics object will include the electromagnetic attribute settings of the model, such as the excitation coil settings, electromagnetic model selection, etc. For example, using the aforementioned "geom1" geometric model in the model to create a Physics object named "magfield" electromagnetic field, the relevant code is

```
Physics mag;
mag=model.physics().create("magfield","InductionCurrents","geom1");
```

The relevant code for establishing the coil and setting the parameters in the model is

```
PhysicsFeature cl;
cl=mag.feature().create("coil1","Coil",2); //Create coil object
with(cl);
set("ConductorModel", "Multi"); //Set the type to multi-turn coil
set("coilGroup", true); //Create a coil group
set("ICoil", 3]); //Set the coil current (3A)
set("N", 80); //Set the number of coil turns (80)
endwith();
```

Material object

This object contains the material properties used for simulation. For example, if the BH curve data required for a material is not provided in Comsol, it can be input into the model through the Material object.

Mesh object

This object stores the model grid, including multiple methods such as grid generation and modification.

Study object

The Study object is used to set the solution type and solver parameters.

Result object

This object stores calculation data and provides multiple methods such as display and output of calculation results.

5. Design calculation example

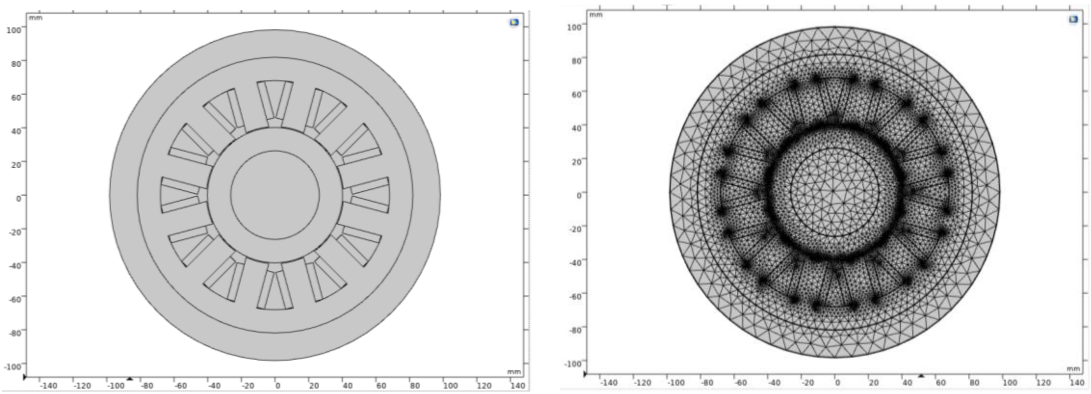
The input parameters required for a certain C-type electromagnetic bearing are shown in Table 1. After calculation by the software described in this article, the obtained parameters are shown in Table 2. The bearing geometry structure established by the software using the API provided by Comsol is shown in Fig. 6(a), and the mesh model obtained by the mesh method is shown in Fig. 6(b).

Table 1 Calculation input parameters

B_{max}	1.2T	j_{max}	6A/mm^2
c_0	0.5mm	k_c	0.4
i_0	3A	i_{max}	6A
R_o	82mm	k_l	0.95
F_{max}	1200N	N_p	12

Table 2 Calculation output parameters

R_m	68.11 mm	R_i	40.73 mm
r_o	40.23mm	r_i	26.34 mm
t	13.89 mm	h_p	27.38 mm
c_w	4.51 mm	c_l	22.57 mm
d_c	1.128 mm	L	82.18 mm
N	80		

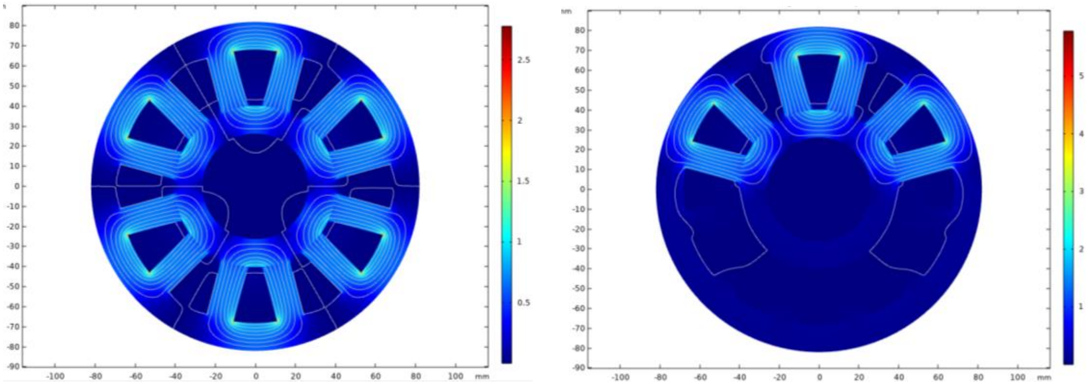


(a) Geometry (b) Grid

Figure 6 Bearing model

Fig. 7 shows the magnetic field distribution of bias current excitation and maximum current excitation calculated by software. It can be seen that the magnetic bearing magnetic field distribution obtained after software calculation and automatic modeling and analysis process is reasonable.

In order to verify whether the designed bearing meets the bearing capacity requirements, the program uses Comsol to integrate the Maxwell stress of the rotor to obtain the electromagnetic force received by the rotor. Table 3 lists the maximum electromagnetic force on the rotor of C-type electromagnetic bearings with different numbers of magnetic poles under the maximum excitation current with the same input parameters (see Table 1). It can be seen that when the number of magnetic poles is different, the maximum bearing capacity F_max of the designed electromagnetic bearing meets the design requirement of 1200N, which shows that the algorithm and program are reasonable.



(a) Bias current excitation (b) Maximum current excitation

Figure 7 Magnetic field distribution

Table 3 Maximum bearing capacity of C-type electromagnetic bearings with different numbers of magnetic poles

Number of magnetic poles	Maximum electromagnetic force (N)
8	1273.2
12	1347.9
16	1286.6

The calculation method of E-type radial electromagnetic bearing is similar. Using the input parameters in Table 1, calculate the electromagnetic field distribution of the E-type electromagnetic bearing with 12, 18 and 24 magnetic poles, as shown in Fig. 8. It can be seen that the magnetic field distribution is also reasonable.

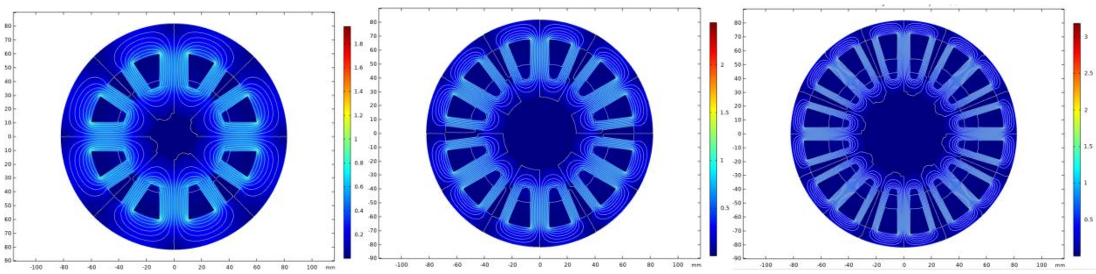


Figure 8 E-type electromagnetic bearing magnetic field distribution

6. Conclusion

This paper discusses the realization of the design and analysis system for radial magnetic bearings based on Comsol. By integrating the design algorithm into the Comsol software, it is possible to effectively design C-type and E-type radial bearings with different numbers of magnetic poles using some input parameters, and use simulation to verify whether the electromagnetic field distribution and bearing capacity of the bearing are reasonable and satisfied Claim. Through this system, the design efficiency of electromagnetic bearings can be greatly improved, and the engineering application of electromagnetic bearings can be promoted.

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