An Overview of the Thermal Calculation and the Cooling Technology for Active Magnetic Bearing

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Abstract. The cooling process of AMB is that the energy loss is sent out to the outside world when the system is operating. The energy loss transfers to the surrounding medium in the form of heat, which leads to raise the temperature of system components and influences the performance of the system. So it is necessary to study the internal loss of the magnetic bearing system and thermal calculation method. Three kinds of thermal calculation methods are compared, which is important for the design and calculation of cooling. At the same time, the cooling way, the cooling method, and the cooling system is summarized on the basis of cooling technology of active magnetic bearing, and the design method of the cooling system is studied. But for the active magnetic bearing system, when designing the cooling system, heat dissipation of the motor can not be ignored. It is important not only for the performance of the active magnetic bearing system and stable operation, but also for the improvement of the cooling technology.

1. Introduction

Active Magnetic Bearing (AMB) is a typical mechatronic system, which is no contact, wear and lubrication, controlling its dynamic behavior and other series of characteristics[1]. AMB can transform the electrical energy into mechanical energy, which levitates a rotor against gravity. In the process of the running, a certain energy losses will be generated. It leads to raise the temperature of system components and the loss diffused into the surrounding medium in the form of heat. If the cooling is not immediate, the performance of AMB system will be seriously affected. However, since AMBs are complex mechatronic systems, there are many potential power loss mechanisms. The minimizing of losses is the sum of various measures and depends very much on the requirements of the application. In fact, turbomachinery is the main application fields of magnetic bearing. It covers a small turbine vacuum molecular pump, large megawatt of turbine generator and compressor[2].

2. Losses and thermal calculation method in AMB

2.1. Losses

Similar to the motor, analysis of AMB loss and calculating the heat distribution are the important premise for the research of AMB temperature and cooling. Heat sources are related with the system losses. Seen from the Fig.1, the typical spatial layout of magnetic bearing system is represented, but the energy loss distribution of magnetic bearing system is also reflected. The losses mainly include electric loss (copper loss) of the stator, magnetic loss (hysteresis loss and eddy current loss), magnetic loss and aerodynamic losses of the rotor[3,4], as shown in figure 1. In switched amplifiers, switching
losses are dominant. The switching losses are about proportional to the switching frequency and depend on the design of the electronic switches and the properties of the specific switching transistors employed. Ohmic losses in the cables may present a substantial part of the total losses. The losses in the cables have to be covered by the power amplifiers.

**Figure 1.** Distribution of energy loss and the spatial layout of AMB.

### 2.2. Thermal calculation method for AMB

Thermal calculation aims to understand the thermal flow of effective part and temperature distribution in the AMBs. The basic requirement of calculation is the accuracy of the highest temperature and average temperature for the coil. Average temperature is the most suitable operation index, because the highest temperature will limit power under the heat insulation level. Due to heat transfer, the thermal flow travels from the coil heads into the cooling medium, and due to heat conduction, through the insulation between the coil and the iron core. Finally, due to heat transfer, thermal flow travels from the iron core to the air.

#### 2.2.1 Thermal parameter method

According to the principle of superposition, the rise of temperature of the AMB are identified. Assumptions: the calorific value of coil is determined by electric loss $P_{m1}$, the wastage of the coil is constant, which does not depend on other parts of the loss. Under the condition of the same cooling, the stator core and rotor loss $P_2$ and $P_3$ can be determined by using the heating coefficient $k_2$ and $k_3$, see the Eq. (1).

$$
\begin{align*}
\Delta T_{m1} &= R_m P_{m1} \\
\Delta T_{m2} &= k_2 R_m P_{m2} \\
\Delta T_{m3} &= k_3 R_m P_{m3}
\end{align*}
$$

Where $R_m$ is the equivalent thermal resistance. Under the stable thermal state, the total temperature rise calculation by Eq.(2). Thermal parameters method is relatively simple, but because the consideration is not comprehensive, it is suitable for rough calculation in the early design process.

$$
\Delta T_m = \Delta T_{m1} + \Delta T_{m2} + \Delta T_{m3} = R_m(P_{m1} + k_2 P_{m2} + k_3 P_{m3})
$$

#### 2.2.2 Equivalent thermal network method

The graph theory and circuit theory is introduced to combine with the heat transfer principle, and the equivalent thermal network method is developed. The bearing model has been realized as a thermal network. According to the unified form of the heat exchange equation (the Fourier law), which is similar to the ohm's law, Eq. (3) is derived.

$$
P = \frac{\lambda S \Delta T}{\delta} = R_\lambda \Delta T
$$

Where $\lambda$ is the heat conduction coefficient, $S$ is the average area of the heat transfer surface, $\Delta T$ is the temperature rise on the length $\delta$, $R_\lambda$ is the thermal resistance.

Assumptions: the real source of heat and thermal resistance is replaced by a finite number of concentrated heat source and the equivalent thermal resistance. the equivalent thermal resistance does
not change with the size of the thermal flow. As a result, the equivalent thermal network is a linear thermal circuits and algebraic overlay. Thermal resistance is through the medium parameters (the thermal conductivity, the heat capacity, etc.) is identified. In the thermal circuit, temperature depends on the size of the heat source. Figure 2 shows the equivalent thermal network about the radial magnetic bearing. Each pair of coils is regarded as a heat source. Each heat source is represented with the mean surface temperature \( \theta_{cu} \). The bearing is air cooled with a temperature \( \theta_{0} \). \( A_{cu} \) is the thermal conductivity coefficient of the coil head. For the transfer from the iron core to the air \( A_{fe} \) is obtained. For the transfer from the insulation to the iron core \( A_{i} \) is obtained.

![Figure 2. Equivalent thermal network of the radial magnetic bearing.](image)

2.2.3 Finite temperature field method It is based on the solution of the heat conduction differential equation, according to general thermal transfer law these equations are constructed. In differential equations and boundary conditions, using equivalent thermal network thermal contact will be expressed. In equation of the temperature field method the heating temperature of cooling medium and winding groove to make the transition to the end of the structure characteristics have been considered. Through this method the temperature field of magnetic bearing is analyzed. Therefore, the differential method is a good basis to analyze the effect of parameters of the effective part, and effective practical conclusions are concluded. Such as the diameter, the pole angle, the back-iron width on the temperature effect is different. But, in small or micro magnetic bearing, the thermal effect is more significant between different parts, such as the rotor and the stator, the core and the coil, etc. In these cases, therefore, the magnetic bearing of the equivalent thermal network is first recognized, and then each unit by using the method of temperature field is analyzed.

3. Cooling technology of AMB

Cooling medium can be a gas or liquid, the corresponding cooling way is a gas or liquid cooling. Gas may be air, compressed air, hydrogen or helium gas. In different gases, the thermal conductivity coefficients, heat capacity and density are different. Due to the calorific value is smaller for the tiny magnetic bearing, it can be air cooling or natural cooling. WANG Yan, XIE Heng[5,6] have analyzed the cooling system of magnetic bearing in high temperature gas-cooled test reactor. Helium cooling is instead of steam cooling. Because the helium gas has high thermal conductivity coefficient and heat capacity, and the small density, an effective cooling system can be established. Liquid can be distilled water or oil, it takes only a small amount of power to take away a lot of heat, this kind of cooling method has been applied in the large structure of AMBs.

Generally, the running environment is divided into totally enclosed and open for AMBs. When the surrounding environment is open form, the surrounding air is used to blow its heat source such as coil winding, eventually aiming at degrading the operating temperature. Yet this cooling way is not suitable for high humidity, dust, high temperature environment. Therefore, enclosed AMBs is separated by a closed cavity with the outside world. Because air cooling or cooling liquid is filled into a closed cavity in the body, the part of the heat is taken out to achieve the purpose of cooling. When designing cooling system needs to be fluid calculation, determine the flow resistance of the cooling system, pressure loss and flow velocity along the cooling channels, and make up for the loss of the cooling system, suitable coolant flow rate and power is selected. In the initial design, thermal parameter method may be used for the comparison of the different cooling scheme in order to
eliminate unreasonable cooling scheme in preliminary heat calculation. If cooling groove has not been open or it can't satisfy cooling design, then the shaft directly exchange with cooling medium to cool magnetic bearing for heat. The Fig. 3 represents the flow charts of the cooling system design on active magnetic bearing.

Calculation of the ventilation system is to determine the flow resistance, pressure loss and the flow rate of the cooling medium on the cooling system. According to the law of conservation of energy, the flow of cooling medium is determined by thermal calculation. Determining the network features and setting up the equivalent circuit diagram of the cooling system, so it is simple and intuitive to calculate the ventilation system. But for the magnetic bearing system, when designing the cooling system, heat dissipation of the motor can not be ignored. Motor as a product, some manufacturers have to provide the cooling system. However, analysis and calculation of the cooling of the motor need to be for the integration of system design, because the heat coming from the motor is large.

**Figure 3.** Flow charts of the cooling system design for AMB.

### 4. Conclusion

It is helpful for the optimization design of the AMB by studying the energy loss of AMB. Three kinds of thermal calculation methods are compared, which is important for the design and calculation of cooling. The cooling way, the cooling method, and the cooling system are summarized on the basis of cooling technology of active magnetic bearing. But for the active magnetic bearing system, when designing the cooling system, heat dissipation of the motor can not be ignored. It is important not only for the performance of the active magnetic bearing system and stable operation, but also for the improvement of the cooling technology.

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