Study on the Mechanism of Magneto-optical Modulation Temperature

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Abstract. In recent years, magneto-optical modulation has a wide range of applications and good performance in the fields of azimuth transfer, magnetic field measurement, metal surface damage detection, etc. The core technology is to achieve accurate measurement of the angle by applying the polarization characteristics of light. The magneto-optical modulation system based on this principle belongs to a kind of electrical components. When working, it needs to load a certain current excitation, which causes the temperature of the system to rise, which in turn has a certain influence on the electrical characteristics of the device, and even causes the working state of the system to occur. Change, so in practical applications, temperature factors must be considered. On the basis of fully understanding the structure and working principle of the components, the paper makes a reasonable simplification of the overall structure of the equipment, and obtains the research physical model and numerical heat transfer model. The results show that one of the main heat sources of the system when the solenoid coil and the stainless steel bracket are used, the system temperature is getting higher with the increase of working time.

1. Introduction

The temperature field characteristics are the key to the realization of the function of the magneto-optical modulation device. It affects the electromagnetic characteristics and magneto-optical characteristics of the magneto-optical modulation system, and ultimately affects the angular accuracy of the magneto-optical modulation azimuth transmission equipment, and the long-term operating temperature affects the working life of the system equipment, so the study of temperature characteristics can directly affect the pros and cons of the system design determine the pros and cons of the product work. By grasping the temperature characteristics of the system, this paper corrects the calculation formula of the azimuth transmission, so as to add the influence of temperature change, and control the measurement accuracy of the system within the acceptable range to ensure the reliability of the system work. At the same time, the temperature field of the magneto-optical modulation system is analyzed, the temperature characteristics of the system are mastered, and the evaluation method of the temperature field characteristics is found. The basis and reference for the structural design, material selection and azimuth transfer formula correction of the magneto-optical modulation system are provided.
2. Theoretical Model Construction of Temperature Distribution

When the magneto-optical modulation system is in working state, it is necessary to pass a certain excitation current to the modulation coil of the magneto-optical modulator. On the one hand, under the effect of the coil thermal resistance, the energized coil converts a part of the electric energy into Joule heat and is outwardly lost; On the one hand, due to the phenomenon of electromagnetic induction, the energized coil converts a part of the remaining electric energy into a magnetic field, which can form a certain magnetic field distribution in space. When the excitation signal is an alternating current, according to the description of Maxwell's classical electromagnetic theory, the coil There will also be a magnetic field and an electric field alternately distributed in space, and the energy of one excitation current of each part. When a ferromagnetic material exists in the induced electric field, similar to the thermal resistance effect, the eddy current electric field will be generated in the ferromagnetic material. Joule heat, heat is lost to the outside through the material.

2.1. Mathematical model of heat transfers in solenoid

Due to the heat generation mechanism of the coil, the entire five-layer coil cannot be regarded as a whole piece of cylindrical copper material, which should be caused by the presence of the lacquer coating layer in the radial direction and the axis. The direction is discontinuous, so it does not satisfy the assumption that the condition is established - the nature of the same material, but also should consider the air gap existing in the coil winding, the smoothness of the winding, etc, which have a significant impact on the final simulation results [1]. Here we focus on the calculation of the comprehensive thermal conductivity of the enameled wire coil. The temperature gradient distribution in the composite flat wall is shown in Figure 1.

![Figure 1. Step distribution of temperature in different media](image)

According to the principle of energy conservation, in the steady state, the heat received by each medium is equal to the heat transferred to the next medium, that is, the heat output. Based on this assumption, it can be obtained.

\[
\dot{q} = -\frac{k_1}{l_1} A(T_2 - T_1) = -\frac{k_2}{l_2} A(T_3 - T_2) = -\frac{k_3}{l_3} A(T_4 - T_3) = \ldots = -\frac{k_n}{l_n} A(T_{n+1} - T_n)
\]  \hspace{1cm} (1)

When you only care about the temperature difference between the left and right sides when it is stable, there is.
\[ \Delta T = (T_2 - T_1) + (T_3 - T_2) + (T_4 - T_3) + \cdots + (T_{n+1} - T_n) = T_{n+1} - T_1 \]  

(2)

Simultaneously.

\[ T_{n+1} - T_1 = -\frac{\dot{q}_1 l}{k_1 A_1} \]  

(3)

Substituting equation (2) into equation (3) can obtain the relation.

\[ \Delta T = \left( \frac{\dot{q}_1 l_1}{k_1 A_1} + \frac{\dot{q}_1 l_2}{k_2 A_2} + \frac{\dot{q}_1 l_3}{k_3 A_3} + \cdots + \frac{\dot{q}_1 l_n}{k_n A_n} \right) \]  

(4)

Under the previously assumed steady state, \( \dot{q}_n = \dot{q}_{n-1} \) and \( A_n = A_{n-1} \), and there is a comprehensive thermal conductivity, the above equation can be simplified to.

\[ \Delta T = -\frac{\dot{q}_1 \sum_{n=1}^{n} \frac{l_n}{k_{\text{comprehensive}}}}{A_n} \]  

(5)

Can be obtained from equations (4) and (5).

\[ k_{\text{comprehensive}} = \frac{\sum_{n=1}^{n} l_n}{\sum_{n=1}^{n} \frac{1}{k_n}} \]  

(6)

In the coil, the whole coil is regarded as a regular arrangement of copper wire, lacquer backing layer and air. By looking up the table, the thermal conductivity of the three is very different, quantitative span by \( 10^2 \text{ to } 10^5 \text{ (W/mK)} \) [2]. The heat transfer is carried out along the high thermal conductivity path. It is studied to analyze the heat transfer process as a current transfer process, and the whole system is placed in the circuit system to solve the problem. Here, referring to the practice of Document [3], a mathematical model analysis of the coil windings is established from a microscopic point of view.

![Mathematical model of coil winding cross section.](image)

A rectangular area is taken from the winding profile to obtain a material area of
\[
\begin{align*}
A_{Cu} &= 2\pi r^2 \\
A_{\text{insulating paint}} &= 2\pi \left( R^2 - r^2 \right) \\
A_{\text{Air}} &= (4\sqrt{3} - 2\pi)R^2
\end{align*}
\]  

(7)

Then the corresponding equations can be listed (8)

\[
\begin{align*}
L_{Cu} &= \frac{\pi r^2}{2R} \\
L_{\text{insulating paint}} &= \frac{\pi \left( R^2 - r^2 \right)}{2R} \\
L_{\text{Air}} &= \frac{2\sqrt{3} - \pi}{2} R
\end{align*}
\]

(8)

The resulting thermal conductivity of the coil

\[
K_{\text{Comprehensive}} = \frac{L_{Cu} + L_{\text{insulating paint}} + L_{\text{Air}}}{L_{Cu}/K_{Cu} + L_{\text{insulating paint}}/K_{\text{insulating paint}} + L_{\text{Air}}/K_{\text{Air}}} = 19.43 R - 7.846 \frac{r^2}{R}
\]

(9)

2.2. Heat transfer model of stainless steel bracket

According to the description of the electromagnetic field theory in the literature [4] and the calculation of the electromagnetic field after energization of the tight-wound coil, it is more convenient to calculate the eddy current heating power in the magneto-optical modulation device in this study, and establish the column coordinates, as shown in Fig. 3. Show.

Figure 3. Geometric model of iron frame in cylindrical coordinate system.

The outer diameter of the heat generating device is set to \( R_0 \), and the inner diameter corresponds to \( r_0 \); the time harmonic electromagnetic field propagates radially inside the element, and the conducted electromagnetic field and current density can be expressed as

\[
\begin{align*}
\dot{E} &= e_\varphi \dot{E}_0 e^{-\gamma (R_0 - r)} \\
\dot{H} &= e_\theta \dot{H}_0 e^{-\gamma (R_0 - r)} \\
J &= \sigma \dot{E} = e_\varphi J_0 e^{-\gamma (R_0 - r)}
\end{align*}
\]

(10)
Where $\gamma$ is the propagation constant, $E_0$, $H_0$, $J_0$ represents the complex amplitude of the electric field strength, magnetic field strength and current surface of the ferromagnetic device, respectively, and the three satisfy the relationship [5]

$$H_0 = E_0 \sqrt{\frac{\sigma}{2\omega\mu}} (1 - j)$$

$$j_0 = \sigma E_0$$

Available from Equation 10, 11 and Joule’s law

$$P' = \frac{1}{2} \int_V \sigma |E|^2 dV = \frac{1}{2} \int_0^{R_0} \sigma |E|^2 e^{-2\alpha (R_0 - r)} dr = \frac{1}{2} |E_0|^2 \sqrt{\frac{\sigma}{2\omega\mu}} (1 - e^{-2\alpha (R_0 - r)})$$

The above formula represents the heat loss of the heat generating device of volume $V$, Considering that the length of the actual component is $l$, the actual heating power is

$$P = P'S = \pi R_0 |E_0|^2 \sqrt{\frac{\sigma}{2\omega\mu}} (1 - e^{-2\alpha (R_0 - r)})$$

The calculation relationship given by the above formula can be derived as follows: in the case of the geometry and material properties of the conductor, the electromagnetic induction heating power can be obtained from the electric field strength $E_0$, and the formula 14 can be obtained from the magnetic field strength $H_0$ [6], which is

$$H = \frac{\alpha I_0 \cos(\omega t)}{4\pi} \left( \int_0^{2\pi} \frac{\alpha - \rho \cos \theta}{\left( \rho^2 + \alpha^2 - 2\rho \alpha \cos \theta + (\rho \omega/2\pi)^2 \right)^{3/2}} d\theta \right)^{2}$$

Combined 12, 13, you can get

$$P = \frac{R_0 \alpha I_0^2}{8\pi} \sqrt{\frac{\omega \mu}{2\sigma}} (1 - e^{-2\alpha (R_0 - r)}) \left( \int_0^{2\pi} \frac{\alpha - \rho \cos \theta}{\left( \rho^2 + \alpha^2 - 2\rho \alpha \cos \theta + (\rho \omega/2\pi)^2 \right)^{7/2}} d\theta \right)^{2}$$

Heating element attenuation constant $\alpha = \sqrt{\frac{\mu \omega}{2}}$

3. Conclusion

When the solenoid coil of the magneto-optical modulation system is energized into the excitation current, a large amount of Joule heat will be generated due to the thermal resistance effect of the coil. At the same time, the coil is still an inductor, which has an inductive reactance and also consumes electric power to generate heat. When the magneto-optical modulator contains stainless steel firmware, under the action of the alternating magnetic field, the eddy current effect of the metal will occur, accompanied by eddy current loss, and the hysteresis loss will also exist to varying degrees. Therefore, the solenoid coil and the stainless steel bracket are the main heat sources of the system.
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