Thermal-structural Coupling Analysis Based on ANSYS for Optical Feedthrough

Xingxing Luo[1,a] , Huinan Fu[1,b*] , Yuming Dong[2,c]

[1]School of Mechanical and Electrical Engineering, Guangdong University of Technology,
Guangzhou , Guangdong 510006, PR China;

[2]Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen,
Guangdong 518055, PR China

[a]luoxx0109@163.com [b*]hnfu@gdut.edu.cn [c]ym.dong@siat.ac.cn

Keywords: Optical Feedthrough, ANSYS, Thermal-structural Coupling, Thermal deformation

Abstract. Based on finite element analysis, natural convection heat transfer and other theory, we established finite element model of optical feedthrough , and we got the natural convection coefficient of air at 140℃. Through the study of thermal analysis of fiber feedthrough, we got the temperature field distribution and heat flux distribution of the optical feedthrough. Optical feedthrough will produce thermal stress when it is heated. And the thermal stress will affect the performance of optical feedthrough. Consider this real problem, we carried out the thermal-structural analysis further. Then we simulated the thermal deformation in the process of optical feedthrough heating, got the stress field and deformation of optical feedthrough. And we also analyzed whether structural damage will happen when the fiber feedthrough working on the specific temperature. This study provide a basis for the same type structure.

Introduction

In recent years, due to the optical fiber temperature sensing technology have the characteristics of insulation, resistance to electromagnetic interference, high pressure resistance, chemical corrosion resistance, security, etc, compare with traditional temperature measuring method, it was applied more and more in the temperature monitoring of power plants, transformer and other power facilities. Large transformer is usually oil-immersed transformer, the airtight vessel contains a large amount of thermal oil for winding thermal conductivity. Optical feedthrough is an important switching component of optical fiber temperature measurement of high-temperature airtight vessel, it was used to connect optical fiber inside and outside of airtight vessel. Inside the airtight vessel, thermal oil absorb the heat of winding, and then high temperature environment was produced in vessel, the internal high temperature environment transfer heat to optical feedthrough. Outside the vessel, optical feedthrough exchange heat with the air. In this process of heat exchange, optical feedthrough will produce thermal stress. In the long time of high temperature environment, the heat stress may cause optical components of optical feedthrough damage which makes the structure performance degradation. On account of the development of optical fiber temperature sensing is not a long time in domestic, no one has carried out an analysis for such devices. The main research of this paper is to study the thermal deformation of optical feedthrough, and then to predict its effect on the structure performance.

Boundary Conditions of Thermal Analysis

Basic Assumptions. (1) Because of the oil-immersed transformer is a kind of long time work equipment, the internal oil temperature will reach a stable state after a certain time, so we assume that the temperature of the internal oil maintain a constant when it reaches the steady state. The internal stable temperature field as the temperature source. For steady temperature field, the solution question comes down to functional extremum problems [1]:

$$P=\int_V \frac{a}{2}\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2\right]dv+\int_{S_3}\overline{b}\left(\frac{1}{2}T^2-T_aT\right)ds \tag{1}$$

The solution domain is divided into finite element mesh, the temperature function of each unit was obtained by the temperature interpolation of unit node, set the number of nodes to *m*, then, temperature of the unit can be expressed as Eq.2:

$$T(x,y,z)=T(x,h,z)=\sum_{i=1}^{m}N_iT_i=\boldsymbol{NT}^e \tag{2}$$

In the formula: *Ni* (i = 1, 2, … , *m*) is the shape function; ***N*** is the shape function matrix , $\boldsymbol{N}=[N_1\ \ N_2\ \ \cdots\ \ N_m]$; $\boldsymbol{T^e}$ is the element node temperature matrix, $\boldsymbol{T}^e=[T_1\ \ T_2\ \ \cdots\ \ T_m]^T$.

The functional after finite element discrete is equal to the sum of each unit functional, the Eq.1 can be rewritten as Eq.3:

$$\begin{aligned}P=&\frac{1}{2}\sum_e(\boldsymbol{T}^e)^T\int_{V^e}a\left[\left(\frac{\partial \boldsymbol{N}^T}{\partial x}\frac{\partial \boldsymbol{N}}{\partial x}\right)+\left(\frac{\partial \boldsymbol{N}^T}{\partial y}\frac{\partial \boldsymbol{N}}{\partial y}\right)+\left(\frac{\partial \boldsymbol{N}^T}{\partial z}\frac{\partial \boldsymbol{N}}{\partial z}\right)\right]dv\boldsymbol{T}^e\\&+\frac{1}{2}\sum_e(\boldsymbol{T}^e)^T\int_{S_3^e}\overline{b}\boldsymbol{N}^T\boldsymbol{N}ds\boldsymbol{T}^e-\sum_e(\boldsymbol{T}^e)^T\int_{S_3^e}\overline{b}\boldsymbol{T}_a\boldsymbol{N}^Tds\end{aligned} \tag{3}$$

Make $\boldsymbol{h}=\int_{V^e}a\left[\left(\frac{\partial \boldsymbol{N}^T}{\partial x}\frac{\partial \boldsymbol{N}}{\partial x}\right)+\left(\frac{\partial \boldsymbol{N}^T}{\partial y}\frac{\partial \boldsymbol{N}}{\partial y}\right)+\left(\frac{\partial \boldsymbol{N}^T}{\partial z}\frac{\partial \boldsymbol{N}}{\partial z}\right)\right]dv$, $\boldsymbol{g}=\int_{S_3^e}\overline{b}\boldsymbol{N}^T\boldsymbol{N}ds$, $\boldsymbol{f}=\int_{S_3^e}\overline{b}\boldsymbol{T}_a\boldsymbol{N}^Tds$, then, Eq.3 can be rewritten as Eq.4:

$$P=\frac{1}{2}\sum_e(\boldsymbol{T}^e)^T\boldsymbol{h}\boldsymbol{T}^e+\frac{1}{2}\sum_e(\boldsymbol{T}^e)^T\boldsymbol{g}\boldsymbol{T}^e-\sum_e(\boldsymbol{T}^e)^T\boldsymbol{f} \tag{4}$$

In the formula: ***h*** is the unit heat transfer matrix, ***g*** is the contribution matrix of exothermic frontier to heat transfer matrix, ***f*** is the unit temperature load matrix.

(2) One end of the optical feedthrough affected by the constant temperature source, the other side is exposed to the air, and convective heat transfer with air. Due to the large oil-immersed transformer is usually located in the open area, therefore, convection heat transfer between the optical feedthrough and air can be considered as large space natural convection heat transfer.

Boundary Conditions. According to the natural convection experiment correlation formula of large space [2],

$$Nu=C(Gr\ Pr)^n \tag{5}$$

In the formula: *Pr* is the Prandtl number; *Nu* is Nusselt number,

$$Nu=\frac{h\cdot l}{l}\ ; \tag{6}$$

Gr is the Grashof number,

$$Gr=\frac{g.a_n\square t.l^3}{n^2}\ . \tag{7}$$

Dry air thermal physical property parameters of 140℃ under normal atmospheric pressure [2] :

$r=0.854\text{kg/m}^3$, $n=27.8\times10^{-6}\text{m}^2/\text{s}$, $l=3.49\times10^{-2}\,\text{W/(m.K)}$, $Pr=0.684$.

Calculate the Gr value of 2.37×10^4 according to Eq.7, looking for relevant documents know that C=0.48, n=1/4. Plug C and n in Eq.5 to calculate the value of Nu, then, calculate the natural convection coefficient h=10.5W/m^2·K according to Eq.6.

Material Properties. Optical feedthrough is composed of main body, fiber stub and ceramic sleeve. Ceramic and metal are bonded by special glue which is high temperature resistance. Fiber stub and fiber are bonded by the same method. The optical feedthrough is a sealing device. The 3D model is shown in Fig.1. Main body material of the optical feedthrough is 316 stainless steel, material of fiber stub and ceramic sleeve are zirconia (ZrO2) ceramic, optical fiber is quartz (SiO2) material. The material properties[3-5] is shown in Table 1.

Table 1 Material property table

Material	Density [kg/m^3]	thermal expansion coefficient [10^{-6}.K^{-1}]	elasticity modulus [GPa]	Poisson's ratio	thermal conductivity [W/m·K]
316	8000	18.5	206	0.31	16.3
ZrO_2	5890	11.0	220	0.31	2.09
SiO_2	2200	12.3	70	0.17	1.50

Thermal-Structural Coupling Analysis

Contact Settings. Optical feedthrough is a combination of the metal shell, fiber stub and ceramic sleeve, among them, the fiber stub contains ceramic and silica fiber encapsulation in it. Ceramic and main body are bonded by special glue which is high temperature resistance, silica fiber of fiber stub are bonded with ceramic by the same method, no adhesive between ceramic devices. The contact relationship between the various components is set as shown in Table 2.

Table 2 Contact set table

Contact pairs	Contact type
Main part to Ceramic sleeve 1	Bonded
Main part to Ceramic sleeve 2	Bonded
Main part to Fiber stub	Bonded
Ceramic sleeve 1 to Fiber stub	Frictionless
Ceramic sleeve 2 to Fiber stub	Frictionless
Fiber stub to fiber	Bonded

The Finite Element Model. Import the 3D model of optical feedthrough into ANSYS Workbench interface. Set material type and properties of the various components parameters according to Table 1, set the contact type on the basis of contact relationship as shown in Table 2. Use the automatic mesh meshing the body, refinement grid in the contact position, finally, we got 45583 grid nodes and 13106 units.The finite element model is shown in Fig.2.

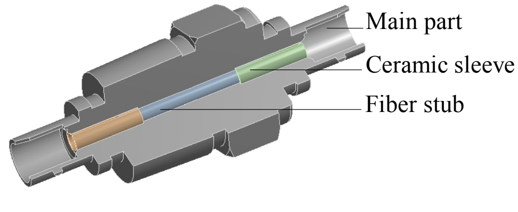

Fig.1 Fiber feedthrough 3D model

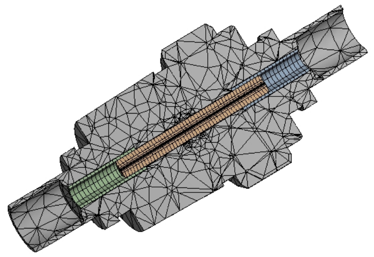

Fig.2. Fiber feedthrough finite element model

Thermal Analysis. Environment temperature set as 25℃, heat source temperature is 140℃, the air natural convection coefficient is 10.5W/m^2·K. Refer to some existing thermal analysis method [6-10], load the temperature parameters on the heated side end face, set the convective heat transfer coefficient. Solution of the steady temperature field is shown in Fig.3, heat flow distribution is shown in Fig.4.

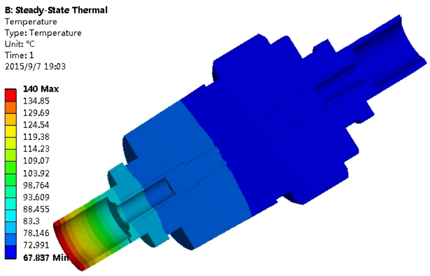

Fig.3. The steady state temperature field distribution

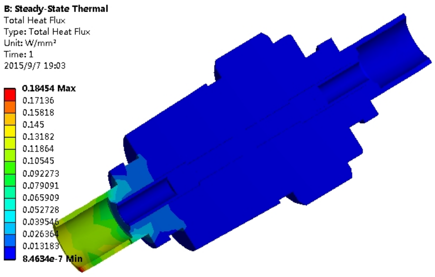

Fig.4. The heat flux distribution

By Fig.3 and Fig.4, we can see that in a simulated environment, optical feedthrough convection heat with air after be heated and temperature reduced gradually along the axial, and the reduce rate increased with the cross-sectional area increased. The cold end temperature is 67.8℃, the heat flow changes from the maximum 0.18454W/mm to the minimum 8.46×10^{-7}W/mm, the heat exchange efficiency is obvious.

Considering the uneven heat produces thermal stress inevitably [11], that cause the thermal deformation. Due to optical feedthrough is a combination of different material components, thermal expansion coefficient of different parts is different, its thermal deformation degree is different also. In order to understand the status of the thermal deformation when the combination is heated, through the thermal-structural coupling analysis to determine the size of the deformation is needed.

Thermal-Structural Coupling Analysis. According to the principle of linear statics, stress and strain meet the following condition as shown in Eq.8：

$$[s]=[D]\{e\} \tag{8}$$

In the formula: $[s]$ is the stress matrix, $\{e\}$ is the displacement matrix, $[D]$ is the elastic matrix.

Optical feedthrough is mainly affected by high temperature environment, the thermal load is the main stress load. In structural analysis, temperature field distribution of thermal analysis in the last step is converted to heat load and imposed on structure of optical feedthrough. Optical feedthrough connect with container body by threaded connection, impose frictionless constraints on the thread area.

After loading loads and constraints, solution of the thermal-structural stress and displacement deformation is shown in Fig.5 and Fig.6.

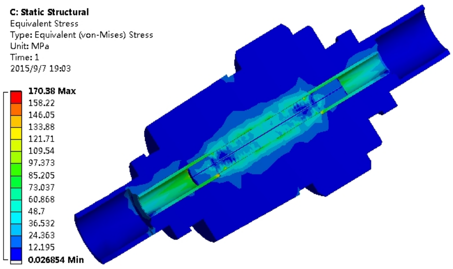

Fig.5. Thermal-structural stress figure

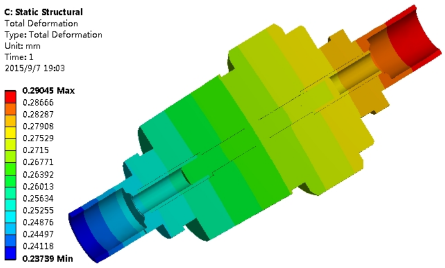

Fig.6. Thermal-structural displacement deformation

From Fig.5, we can see that because of the large difference between zirconia ceramics and metal about thermal conductivity, the residual thermal stress is mainly focused on the internal and surface of ceramics and ceramic edge contact with metal, the maximum stress is 170.38 MPa. Looking up documents, the allowable stress of zirconia ceramics [11] $\left[s_{ZrO_2}\right]$=400MPa, though the ceramic parts are the main position which under thermal stress, but the stress value in the safe range.

From Fig.6, we can see that displacement deformation happened on both axial and normal in optical feedthrough when it be heated, axial is on priority, the maximum relative deformation is 0.29mm, on the cold end part of the main body. The displacement deformation reflect in the axial tensile, for 316 stainless steel[4], the plastic elongation strength $R_p \geq 205$MPa, the tensile strength $R_m \geq 520$MPa, 0.29 mm is a little deformation, the effects of this deformation can be ignored. The ceramic components of optical feedthrough are zirconia ceramic which is a kind of excellent high temperature resistant material with the advantages of high toughness and high bending strength, the small deformation can be ignored. From figure 5 and figure 6, we can see the stress of the optic fiber packaged in optical feedthrough range from 0~12Mpa. According to the study of optical fiber mechanical properties test of the Hairong Liu[12], Peng Han[13], below 300℃, the tensile strength of the fiber range from 2.97GPa to 5.20GPa. This value is greater than the thermal stress of fiber in optical feedthrough when be heated. So for fiber in the optical feedthrough, the influence of thermal deformation on the mechanical properties is very small at 140℃.

Conclusions

Based on the ANSYS thermal analysis of optical feedthrough model, the temperature distribution and heat flow distribution of combination had been solved. The heat flow changes from the maximum 0.18454W/mm to the minimum 8.46×10^{-7}W/mm, these show that the heat exchange efficiency between optical feedthrough and air is obvious at 140℃.The reduce rate increased with the cross-sectional area increased.

On the basis of thermal analysis, converted temperature field distribution solved by thermal analysis to thermal load, and applied it to optical feedthrough structure for the static structural analysis. Through the thermal-structural coupling analysis, the distribution of stress field and displacement deformation law of optical feedthrough had been solved. The maximum stress is 170.38 Mpa on the ceramic parts, this value less than the allowable stress of zirconia ceramics, so the optical feedthrough will be safe.

Under the condition of 140℃ heat source, the thermal deformation of optical feedthrough have little impact on its structure. The maximum stress area is located in the ceramic components, the stress is far less than the allowable stress of zirconia ceramics. Under the condition of this temperature, optical feedthrough will not arise structural damage caused by thermal deformation.

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