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Integrated Optomechanical-Thermal Analysis of Aeronautic Camera Window

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Abstract: In order to improve the imaging performance of aeronautic camera optical system, an analysis of the influence of window glass optical performance caused by the flying environment was conducted. Based on the theory of aerodynamics, the Mach number and Reynolds number were calculated. The flying environment of window was gotten. The heat-transfer model of the camera was established. The heat flow on surface of window was calculated. The temperature distribution was simulated with the Workbench Software. Combined with the force on the window, the surface deformation of the window glass was calculated under the thermal-force coupling conditions. Zernike polynomial was used to fit the surface deformation of window glass with the Sigfit Software. Putting the Zernike polynomial coefficients into optical software, taking MTF as assessment indexes, the influence of deformation of window glass on the imaging performance of optical system was analyzed. The results show that the optical window meets optical performance requirements.

1.Introduction

Window is the important part of the aeronautic camera, and is the interface of the camera with the flying environment. Window is mainly composed of window glass, pressure plate and bracket. During the camera working, the outer surface of the camera will be affected by airflow and air pressure. Window glass can protect the optical system and isolate the outside bad environment. In addition, window glass is the zero light focal optical element, and is the simplest element. Its optical properties directly affect the resolution and the image quality of the camera. The changes of the camera's flight temperature and barometers will deform the window glass, causing changes with the surface of the window glass, at last, affecting the imaging quality of camera optical system.

At present, the domestic and international study of the window mainly focuses on strength analysis, thickness design and thermal optical analysis. Fan da[1] analyzed the influence on the optical window surface deformation caused by the different flying altitudes environment, and the thickness of optical window was well designed.

Thermal-optical evaluation to optical window surrounding hypersonic was analyzed by Zhang hongwen[2]. The influence of thermal deformation of the optical window on optical transfer function was analyzed. Transient state temperature field with thinking only of the convection heat transfer coefficient on outer surface of optical window glass was emulated by Li yanwei[3]. And the optical path in peak to Valley value(PV) and root mean square(RMS) error with the different thickness were calculated under thermal-force coupling condition. Thickness of the window glass was optimized.

Thermal-optical properties of window were analyzed. In order to calculate temperature distribution of optical window within a work cycle, heat flux was assigned on a scale of weight to outer surface of the window and radiation of the window was taken into account by Shi jinfeng[4]. The deformation of window glass at a specified temperature field and pressure field and boundary conditions was calculated by the finite element analysis software. On the condition of high Maher, the influence of temperature and pressure to the optical properties of the optical window were analyzed by Wang naixiang[5]. Based on the fracture mechanics analysis, the glass thickness of the optical window of an airborne multispectral camera was analyzed and designed. The thermo elastic analysis for the windows glass was carried out for the specified circumferential, radial and axial temperature differences and temperature level by Ding yanwei[6]. Based on the thermal optical analysis, the glass thickness of optical window under the complex environment was optimized by Li Ming[7]. The method of calculating heat distortion and OPD was put forward when heat grads influences optical window. And the intensity of optical window using heat and pressure was analyzed[8].

This paper combines the window of aeronautic camera, depending on the camera's flying environment, the convection heat transfer coefficient and pneumatic heat flow density, radiation heat flow density on outer surface of optical window glass is calculated. The temperature distribution is simulated with the Workbench software. Combined with the force on the window, the surface deformation of the window glass is calculated under the thermal-force coupling condition. Zernike polynomial is used to fit the surface deformation of window glass with the Sigfit software. Putting the Zernike polynomial coefficients into optical software, the influence of deformation of window glass on the imaging performance of optical system is calculated. It will provide theoretical reference for window glass optimization design and thermal control.

2.Structural composition of window

As show in Figure 1, camera window mainly consists of window bracket, window glass and pressure plate.

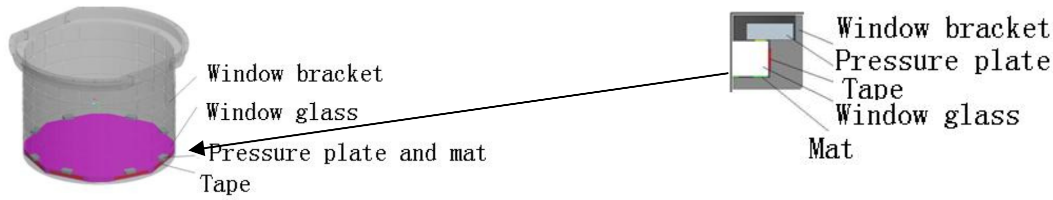

Figure 1.Structure of window

Window glass upper and lower surface is separated by mat. The perimeter is secured with tape. Window glass is made of fused silica with small density, small coefficient of linear expansion, and strong temperature adaptable. The material properties of camera window as show in table 1.

Table 1.Material properties of camera window

Name	Material	Modulus of elasticity Mpa	Density $kg\cdot m^{-3}$	Poisson ratio	Specific heat capacity J/(kg·℃)	Coefficient of linear expansion 10^{-6}/℃(20℃)	Thermal conductivity W/m·℃
window glass	Fused silica	75000	2.2	0.165	787	0.55	1.4
window bracket, pressure plate	Aluminium	72000	2.74	0.33	920	23.1	125
mat, tape	XM23 glue	2.5	1.49	0.48	1700	250	0.287

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3.Outer environment conditions of window

The outer thermal environment of camera window is related to atmospheric temperature, pressure, density, dynamic viscosity and flight Mach number, and other factors. The camera is placed at the bottom of the airplane. There is a circular opening at the bottom. The camera is exposed to the atmosphere. There is a gas exchange between the outside and inside of the airplane. The flight altitude is 1km～3km. The signature height is 3km. The physical characteristics of aerosphere at 3km altitude as show in table 2.

Table 2.Physical characteristics of aerosphere at 3km altitude

Parameters	Value
Atmospheric temperature(T)/℃	-12.5
Atmospheric pressure/Pa	70000
Atmospheric density(ρ)/ $(\mathrm{kg}\cdot\mathrm{m}^{-3})$	0.9
Dynamic viscosity (μ)/ $(10^{-5}\cdot\mathrm{kg}\cdot\mathrm{m}^{-1}\cdot s^{-1})$	1.514
Thermal conductivity(λ)/ $(\mathrm{W}\cdot\mathrm{m}^{-2}\cdot K^{-1})$	0.02

The formula of flight Mach number is:

$$Ma = \frac{\upsilon}{c} \tag{1}$$

The formula of acoustic velocity:

$$c = 20\sqrt{T} \tag{2}$$

Among equation (1) and (2), υ is the flight speed of the airplane relative to the atmosphere; c is the sound of the atmosphere at flying altitude. T is the thermodynamic temperature of the air. T is 260K. Bring the number into the formula, the flight mach number is:

$$Ma = 0.217 \tag{3}$$

According to the flight practice, the Ma value is small and the velocity change will not cause the gas temperature.

The formula of Reynolds number is:

$$\mathrm{Re} = \frac{\rho\upsilon l}{\mu} \tag{4}$$

ρ is the density of the atmosphere; υ is the flight speed of the airplane relative to the atmosphere; υ is $70m/s$; μ is the dynamic viscosity of the air. l is $0.37m$. Bring the number into the formula, the Reynolds number is:

$$\mathrm{Re} = \frac{\rho\upsilon l}{\mu} = 1.54\times10^{6} \tag{5}$$

4.Temperature field analysis of window

4.1 Heat transfer model of window

Heat transfer model of the camera window is shown in figure 2.

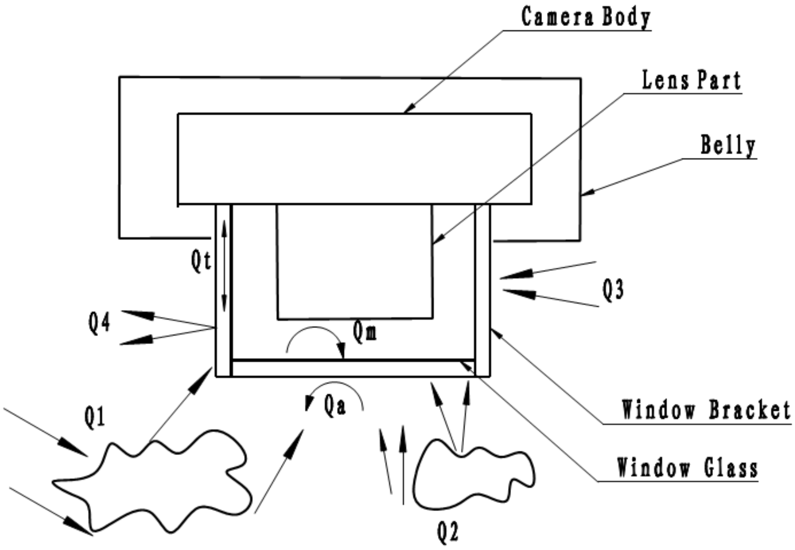


Figure 2.Thermal environment of window

Equation of heat balance is:

$$\rho c \frac{\sigma T}{\sigma t} = Q1 + Q2 + Q3 - Qt - Q4 - Qa - Qm \tag{6}$$

In the form, Q1 is the reflection of solar radiation through the ground and clouds. Q2 is the thermal radiation of the ground and clouds. Q3 is the direct thermal radiation of the sun. Qt is the conduction of heat transfer between the window and the camera body. Qa is convective and pneumatic heat between windows and the astrosphere. Q4 is the heat radiated from the window. Qm is convection heat transfer between windows and camera internal lens components.

Because the camera is mounted in the airplane's abdomen, so Q3=0. The temperature difference between the window and the camera is very small. The influence of the radiation transfer is ignored. The thermal environment around the window is changing, so the equilibrium is a dynamic balance process. Transient thermal simulation is needed.

4.2 Thermal radiation of the window

The thermal radiation of the camera window is mainly from the solar radiation and the heat radiation and the reflection on the ground, including clouds. The window of the camera hangs at the bottom of the airplane, avoiding solar radiation with the highest heat flow density. Therefore, the external radiation heat flow is mainly from the reflection and the thermal radiation of the earth-atmospheric system. Radiation heat flow varies with the changes of the flight height. Taking a typical altitude, H=3km. The steady- state flight with the Mach number Ma=0.2 and the typical flying altitude H=3km is analyzed.

Average albedo of the earth in the thermal design is $R = 0.35$. The average solar constant is $S_0 = 1353W / m^2$. Therefore, in the 3km high-altitude, camera window receives the reflection radiation of the earth-atmospheric system is:

$$q1 = \frac{S_0 R}{4} = 118 \mathrm{W} / m^2 \tag{7}$$

The thermal radiation of the earth-atmospheric system consists of long-wave radiation from the ground through the atmosphere and the atmosphere itself [9].

$$q2 = (1 - A_1)\sigma T_g^4 + A_1 \sigma T_a^4 \tag{8}$$

Type in: A_1 is the average absorption rate of atmosphere long wave. $A_1 = 0.8$; σ is Boltzmann constant; T_g is the average temperature of the earth; $T_g = 288K$; T_a is the atmospheric equivalent temperature; $T_a = 247.7K$, so, obtain: $q2 \approx 248W / m^2$.

The outer surface of the camera window to the irradiance of the atmosphere is:

$$q4 = (\varepsilon_1 + \varepsilon_2)\sigma(T_w^{\ 4} - T_\infty^{\ 4}) \tag{9}$$

Type in: ε_1 is the surface emissivity of the window bracket. $\varepsilon_1 = 0.4$; ε_2 is the surface emissivity of the window glass. $\varepsilon_2 = 0.8$; σ is Boltzmann constant; T_w is the surface temperature of the window; T_∞ is the temperature of the flight environment;

Radiation heat flow density of the window surface as follows:

$$Qr = Q_1 + Q_2 - Q_4 = (\bar{\alpha}_1 + \bar{\alpha}_2)q_1 + (\alpha_1 + \alpha_2)q_2 - Aq_4 \tag{10}$$

Type in: $\bar{\alpha}_1$ is the absorption rate of the outer surface of the window bracket to short wave radiation. $\bar{\alpha}_1 = 0.4$; $\bar{\alpha}_2$ is the absorption rate of the outer surface of the window glass to short wave radiation. $\bar{\alpha}_2 = 0.85$; α_1 is the absorption rate of the outer surface of the window bracket to long wave radiation of the earth-atmospheric system. $\alpha_1 = 0.35$; α_2 is the absorption rate of the outer surface of the window glass to long wave radiation of the earth-atmospheric system. $\alpha_2 = 0.8$; A is the superficial area of the window.

4.3 Heat convection of the window

As shown in figure2, during the camera working, the camera body is inside the belly. Some parts of the window bracket are exposed in the atmosphere. The heat transfer between the outer surface of the window bracket and the atmosphere is a ravage single-pipe fluid heat transfer [10]. According to the average heat transfer coefficient on the surface of the ravage single-pipe fluid as follows:

$$Nu = C\,\mathrm{Re}^n\,\mathrm{Pr}^{1/3} \tag{11}$$

Type in: Re is the formula of Reynolds number. $\mathrm{Re} = 1.54 \times 10^6$; Pr is the Plant constant. $\mathrm{Pr} = 0.172$; $C = 0.026$, $n = 0.805$

Calculate：

$$Nu = C\,\mathrm{Re}^n\,\mathrm{Pr}^{1/3} = 1785.46W / (m^2 \bullet K) \tag{12}$$

Window glass is directly exposed in the atmosphere. The heat transfer between window glass and the atmosphere is the forced convection transfer of fluidized objects. When the atmosphere passes through window glass, because of the resistance of surface friction, laminar flow and turbulent flow are generated at different places on the surface. The heat transfer coefficient between fluid and object is different in different flow state. According to the ravage planomural theory, the average convection heat transfer coefficient of the window glass is calculated [11]. According to the ravage boundary layer theory, the heat transfer coefficient between laminar flow and turbulent flow is determined by the following Nussel criteria:

Laminar flow conditions：

$$Nu = \frac{h_x x}{\lambda} = 0.332\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \quad (\mathrm{Re} < 5 \times 10^5, 0.6 < \mathrm{Pr} < 50) \tag{13}$$

Turbulent flow conditions：

$$Nu = \frac{h_x x}{\lambda} = 0.0296\,\mathrm{Re}^{4/5}\,\mathrm{Pr}^{1/3} \quad (\mathrm{Re} > 5 \times 10^5, 0.6 < \mathrm{Pr} < 50) \tag{14}$$

Type in: h_x is convection heat transfer coefficient; λ is thermal conductivity of the air; $\lambda = 0.02\mathrm{W}/(\mathrm{m}^2 \bullet K)$; Re is the formula of Reynolds number. $\mathrm{Re} = 1.54 \times 10^6$; Pr is the Plant constant. $\mathrm{Pr} = 0.172$;

According to the ravage boundary layer theory, in the case of fluidized flats, the critical thunder number is generally used as the criterion for turbulent flow. The forepart of the window glass is laminar flow, and the back of the window is turbulent flow. In engineering calculations, average surface heat transfer coefficient is often used. As follows:

$$h = \frac{1}{l}\left(\int_0^{x_c} h_x dx + \int_{x_c}^{l} h_x dx\right) = 0.037\frac{\lambda}{l}\left(\mathrm{Re}^{0.8} - 23500\right)\mathrm{Pr}^{1/3} \tag{15}$$

Inputting values, the average heat transfer coefficient of window glass outer surface is obtained.

$$h = 117.2W/(m^2 \bullet K) \tag{16}$$

4.4 Temperature field analysis of window

The finite element model of window component is established by using finite element analysis software workbench, and the grid is divided. The result is shown in figure 3. There are 586150 nodes and 198227 elements. Radiation heat and convective heat transfer coefficient were obtained based on the previous heat transfer model. Temperature field analysis of window is calculated. The result was loaded on the window glass as a temperature load. Thermal deformation of window glass is calculated. The inside of window and the lens are natural convection heat transfer. And the convection heat transfer coefficient is 0.05. Window bracket is connected to the main support plate of the camera body. So the temperature of window bracket top face is 20 degrees Celsius. The thermal boundary conditions of the window are applied as shown in figure 4.

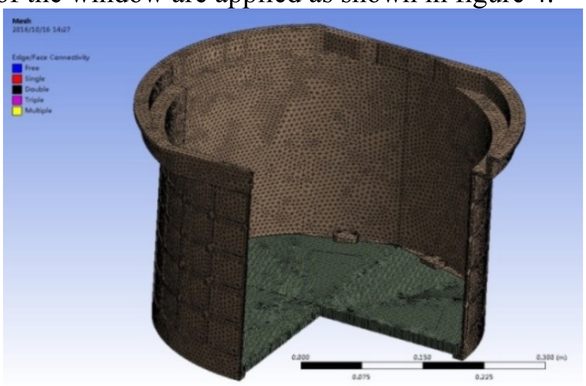


Figure 3.Element model of the window

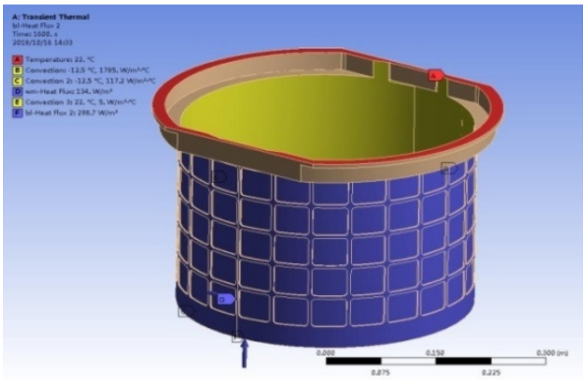


Figure 4.Thermal boundary conditions

The temperature field distribution of the window glass is calculated as shown in figure 5 and figure 6.

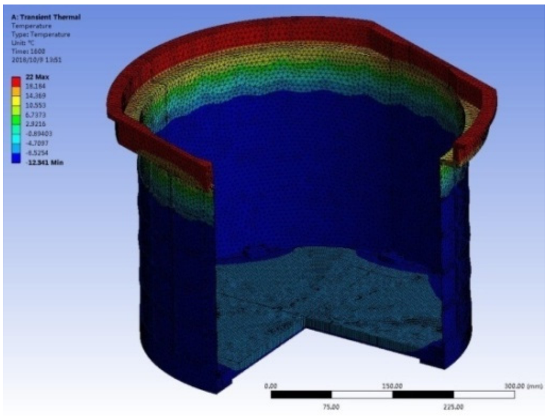


Figure 5. Temperature distribution of window in 1600s

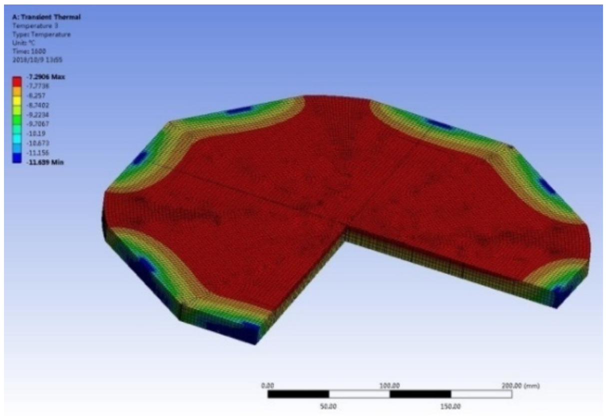


Figure 6. Temperature distribution of window glass

Transient temperature distribution of window glass is calculated in 1600s. Temperature curve of inside and outside of window glass as shown in figure 7.

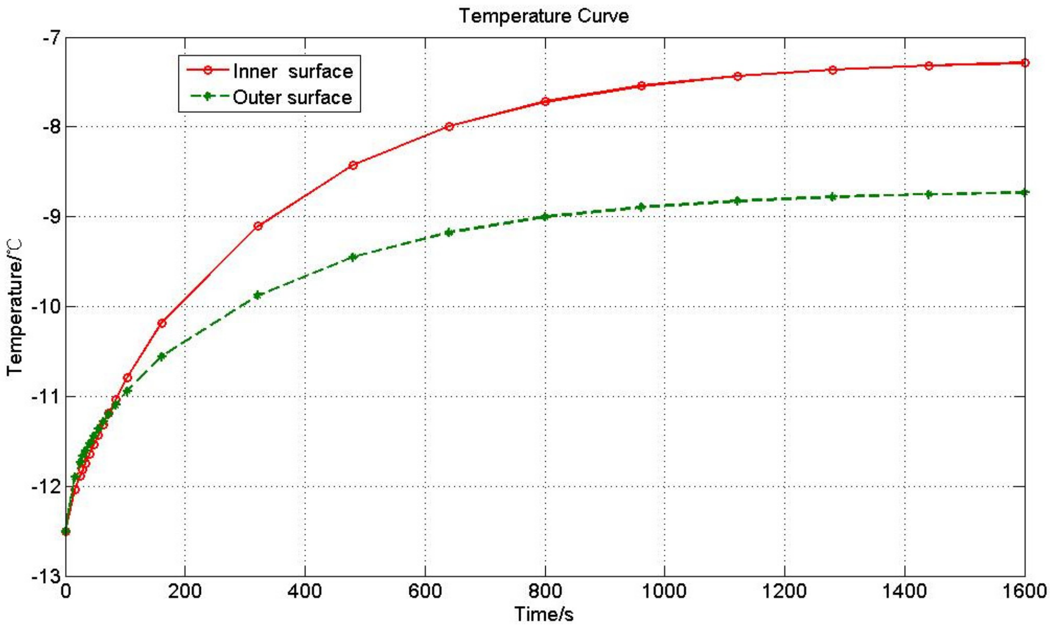


Figure 7.Temperature curve of inside and outside of window glass

As shown in figure 7. Initially, the inner and outer surface temperature of window glass is the same. As the flight time increases, the temperature rises. The inner and outer surface temperature is balanced at the 1600s. The inner surface temperature is -7.2 degrees. The outer surface temperature is -8.5 degrees. The maximum temperature difference on the inner and outer surface occurs at 1600s. The maximum temperature difference is 1.3 degrees.

5.Thermal-forced coupling analysis of window

When the camera is working at the high altitude, the window's inner and external pressure difference, gravity and temperature gradients deform the surface of window glass[5]. And it affects the quality of the camera. The temperature field result of maximum temperature difference is applied to the window glass together with mechanical load. Through simulation, the deformation of window glass is obtained. As shown in figure 8.

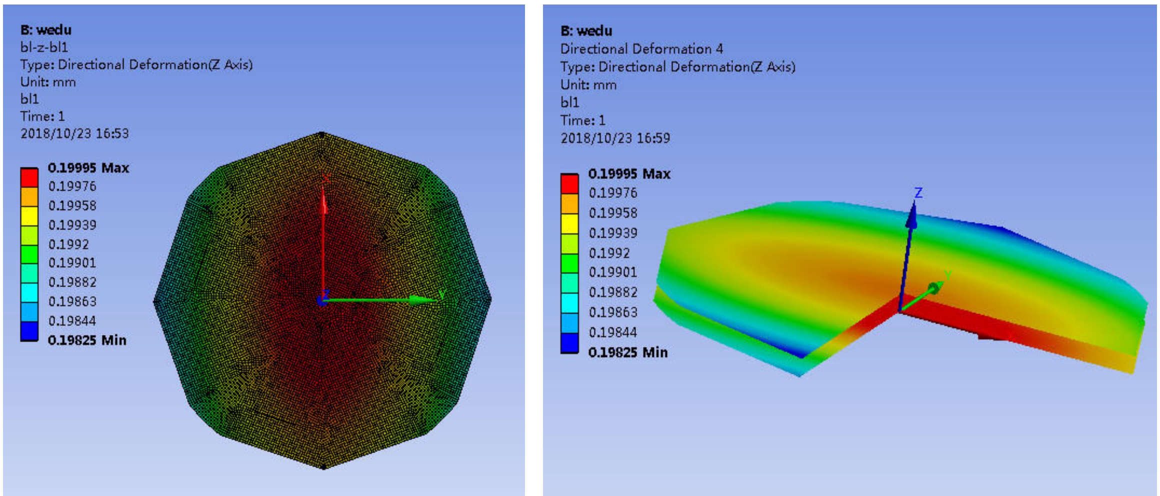


Figure 8.The deformation of inside and outside of window glass cloud chart

6.The affection of window on image quality

The surface deformation of window glass can affect the wave-front aberration of camera optical system. The image quality of camera is affected. According to the obtained surface deformation data of window glass, Zernike polynomial is used to fit the inner and outer surface of window glass with the Sigfit Software. And the polynomial coefficients are obtained. Putting the Zernike polynomial coefficients into optical software, the imaging performance of optical system is analyzed [12].

6.1 Face type calculate

According to the simulation result of the surface deformation of window glass, Zernike polynomial is used to fit the surface deformation. And top 10 Zernike coefficients of internal and external surface on window glass are obtained, as shown in table 3. Removing rigid body displacement, the face type data of window glass is calculated. The PV is 13.5nm. And the PV≤1/40λof optical design requirements is satisfied (λ=632.8nm).

Table 3.Top 10 Zernike coefficients of internal and external surface on window glass

No	Expression	Meanings	Inner surface	Out surface
1	(1)	Constant	0.9594	0.882
2	$\rho\cos\theta$	X Lateral shift	-1.54	-1.47
3	$\rho\sin\theta$	Y Lateral shift	-0.0755	0.113
4	$2\rho^2-1$	Defocus	21.7	21.7
5	$\rho^2\cos 2\theta$	0° Or 90° Astigmatism	-27.7	-27.7
6	$\rho^2\sin 2\theta$	$\pm 45^\circ$ Astigmatism	0.000316	-0.00115
7	$(3\rho^2-2)\rho\cos\theta$	X Axis third order coma	-16.7	-16.7
8	$(3\rho^2-2)\rho\sin\theta$	Y Axis third order coma	0.000295	-0.000188
9	$\rho^3\cos 3\theta$	X Pri Trefoil	4.949413146	3.281232041
10	$\rho^3\sin 3\theta$	Y Pri Trefoil	-0.407893603	-0.457669916
11	$1-6\rho^2+6\rho^4$	Pri Spherical	-1.59	-1.59

6.2 Face type changes on influence of image quality

Perfect optical system is as shown in figure 9. MTF curve of optical system without considering deformation of window glass is as shown in figure 10. The face type data of window glass caused by thermal-forced load are putted into the perfect optical system for calculation. MTF curve of the system with deformation of the window glass is obtained, as shown in table 4. The quality changes are shown in figure 11. Figure 12 shows the shape of the inner and outer surface with after the deformation.

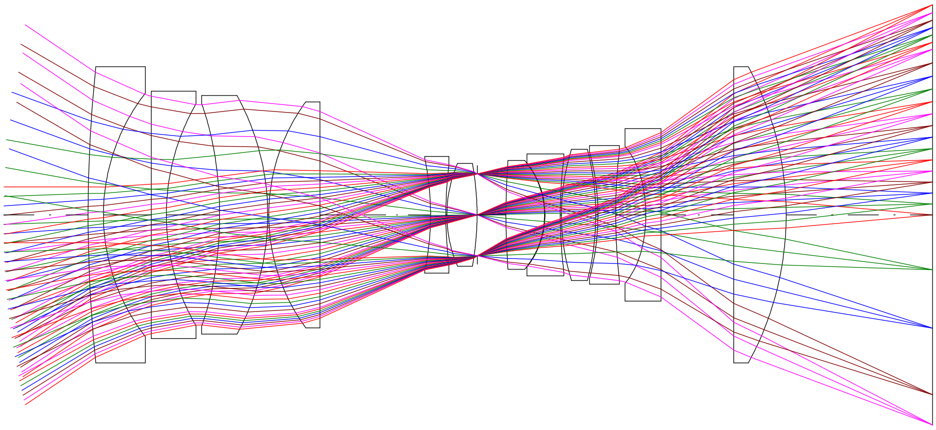


Figure 9.Perfect optical system of f=142

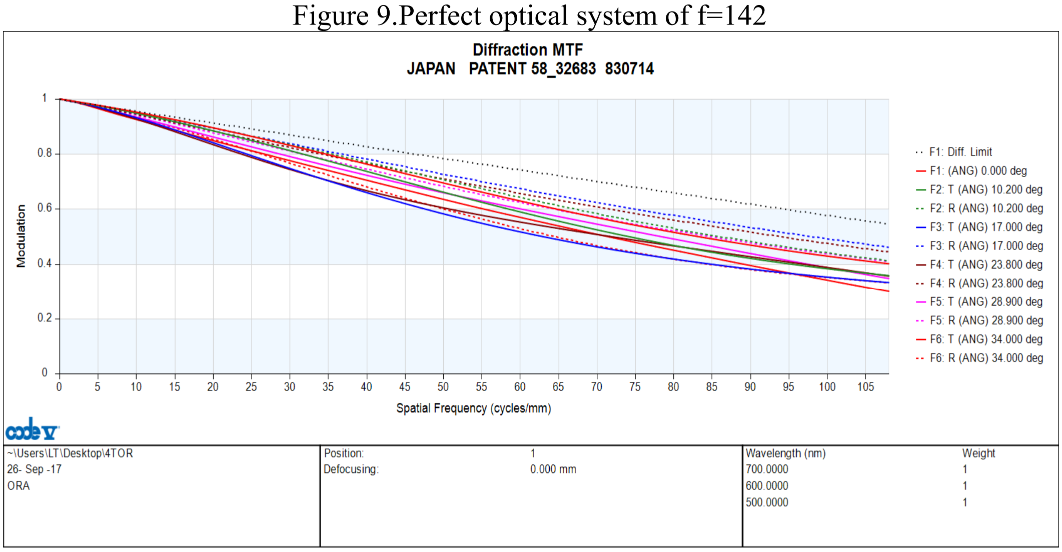


Figure 10.MTF curve of perfect optical system

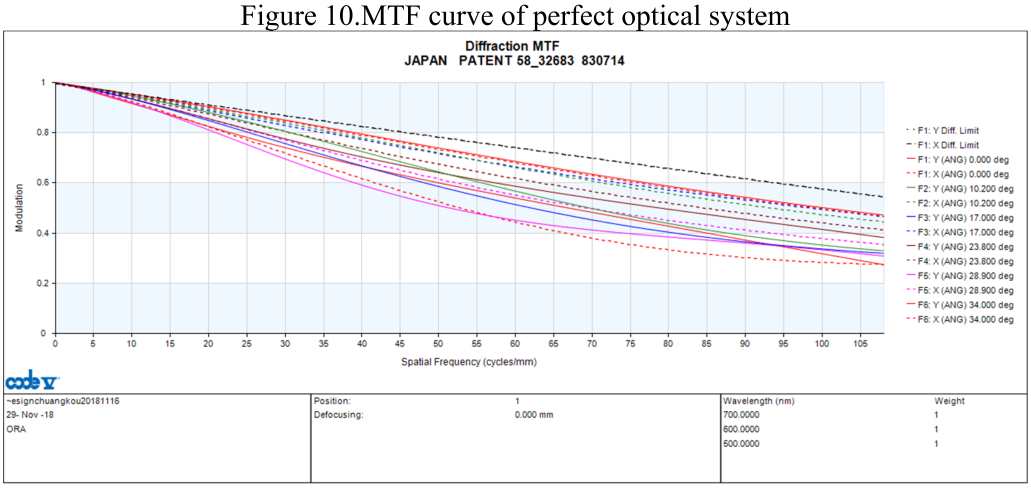
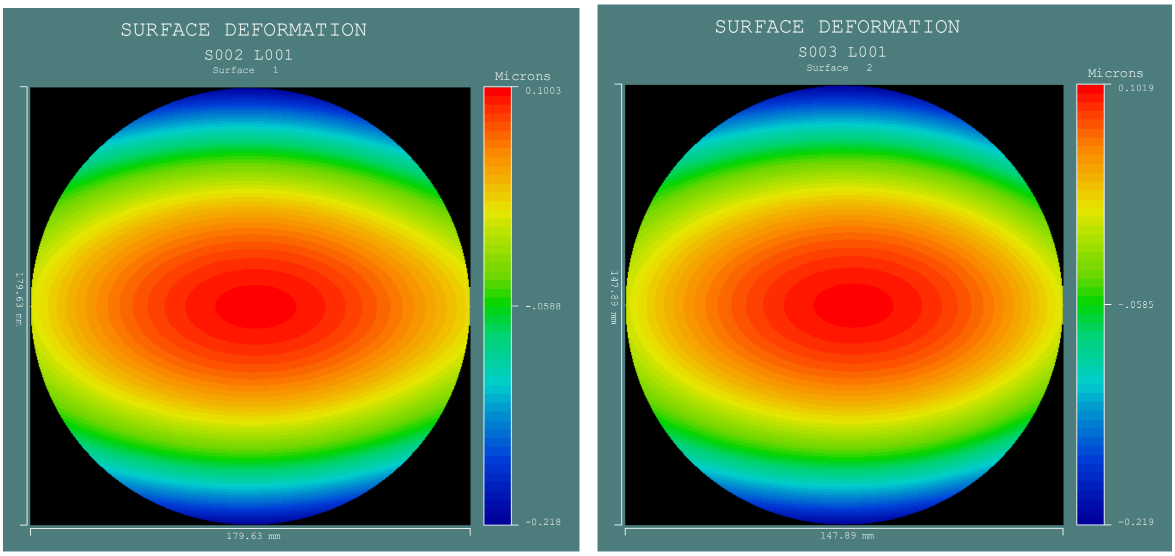


Figure 11.MTF curve of the system with deformation of the window glass



a) Internal surface deformation b) External surface deformation

Figure 12.Fitting surface deformation after the deformation of the window glass

Figure 10, figure 11 and shows that, after the ideal optical system with putting into the changes of window glass surface, MTF values of different visual fields in the optical system are up and down. This is because the window glass is a very small light focal lens after the glass with deformation. After adding this tiny light focus, image aberrations of the original optical system at some fields and some directions are compensated. At the same time, other directions and field of vision increase. So the changes of MTF values in each fields are different. There is a rise and a drop.

The data in the table 4 are the MTF values after the window glass wave-front is introduced (T and S represent Tangential and Sagittal respectively). The comparison shows that the maximum drop in MTF is 0.071(absolution). Because of the small change, the influence of window deformation on imaging performance can be ignored. So the thickness of window glass is designed to be 20mm reasonable.

Table 4.MTF value and its D-value of the system of four fields at Nyquist frequency

MTF at 108lp/mm	Field:0°		Field:10°		Field:23.8°		Field:34°	
	T	S	T	S	T	S	T	S
Original	0.42	0.42	0.43	0.35	0.425	0.34	0.351	0.260
Add wave-front	0.48	0.47	0.49	0.35	0.41	0.385	0.28	0.27
Change value	0.06	0.05	0.06	0.0	-0.015	0.045	-0.071	0.01

7.Conclusion

For the 3 km flight altitude and 0.217 Mach flight speed environment of aeronautic camera, the aeronautic camera window is taken as research object. Based on the theory of aerodynamics, the Mach number and Reynolds number are calculated. The flying environment of window is gotten. The heat-transfer model of the camera is established. The heat flow on surface of window is calculated. The temperature distribution is simulated with the Workbench Software. Combined with the force on the window, the surface deformation of the window glass is calculated under the thermal-force coupling condition. Zernike polynomial is used to fit the surface deformation of window glass with the Sigfit Software. Putting the Zernike polynomial coefficients into optical software, taking MTF as assessment indexes, the influence of deformation of window glass on the imaging performance of optical system is analyzed. The thermal optical evaluation of window glass is realized. At last, combined with thermal optical analysis, the reasonable thickness of window glass under the flight condition is designed as 20mm. The results show that the window glass meets optical performance requirements.

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