Research on wavefront error of prism induced by thermoelastic distortion

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To meet the design and usage requirements of the precision light beam scanner, the thermoelastic distortion of prism is detailedly analyzed by the thermal-structure coupling method, the influence of which, on the surface deformations of prism, is conclusively proved far greater than that of only the gravity load without temperature fluctuation. With the temperature fluctuation from 20 to 20.5 °C, the strains as well as the stresses appropriately eightfold increase, which right accords with the actual results measured by Zygo Mark interferometer with the error of not over 10%. Therefore some strict temperature-controlled measures are necessary for the scanner.

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The scanner of light beam deflection with high accuracy, used to test the performance of pointing and tracking in intersatellite communications[1−3], usually is located in somewhat thermal environment. Therefore, the influence of environment temperature on the key optical components, especially the circular prism, must be strictly taken into account. As the environment temperature fluctuates, the internal temperature gradient of prism formed by the heat conductivity and the inhomogeneous heat interchange not only causes the change of refractive index gradient, but also induces the inhomogeneous heat expansion by reason of the internal heat stress, which always leads to both the distortion of prism and the reduction of physical accuracy. There are usually some typical heat effects[4], such as the edge effect caused by inhomogeneous temperature change, the deformation of mirror surface induced by the inner temperature gradient, the gradient effect of outside atmosphere reflective index and so on. However, applied in a temperature-controlled laboratory, the scanner is mainly affected by its inner temperature gradient[5]. In this paper, we take a circular wedge prism with 380-mm diameter used in a laser beam scanner as an analysis model, and only discuss its thermoelastic distortion induced by the inner temperature gradient and gravity, which belongs to thermal-structure coupling problem. The method of sequence coupling field analysis is adopted. Firstly the thermal analysis is made, then the row vector of solved node temperature, as the body load, is forced into the structure analysis, and finally the thermal-structure coupling is performed.

We build and assemble the precise models of the prism and mounting parts in the scanner by Pro/Engineer, and obtain the corresponding geometry parameters and physical parameters (for example weight, volume, barycenter position, inertia moment and so on). The finite element model is shown in Fig. 1. The material of circular wedge prism is K9 glass, the exiting aperture is ϕ350 mm, the wedge angle is 6°, and the thickness of the thinnest end is 25 mm; the prism with thick end downwards (along the negative direction of z axis) and plane side vertically is nested in a frame, namely a semicircular radial support on the thick end, the looping support is mounted along the axial direction (namely y direction), and the acceleration 9.81 m/s^2 of gravity points to the negative direction of z axis, namely from the thin end to the thick one[6−8].

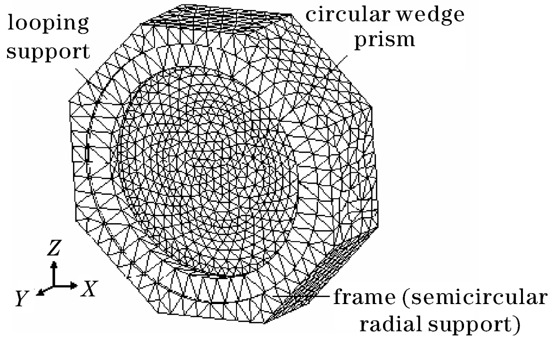

Fig. 1. Finite element model of prism and mounting parts.

Table 1. Strains and Stresses on the Surface of Prism under the Gravity Load without Temperature Fluctuation

	Maximum Deformation (nm)	Mininum Deformation (nm)	P-V (nm)	RMS (nm)	Maximum Stress (MPa)
Plane Side	13.0130	1.2130	11.80	3.4660	0.0385
Wedge Side	12.9940	1.3420	11.6520	3.4530	

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Table 2. Surface Deformations of Prism with the Temperature Fluctuation

	ΔT/°C	Maximum Deformation (nm)	Minimum Deformation (nm)	P-V (nm)	RMS (nm)
Plane Side	0.025	20.5160	0.6130	19.9030	5.3417
	0.05	28.7840	0.8704	27.9136	7.3453
	0.25	79.8890	2.8180	77.0710	19.2160
	0.50	166.8430	6.3870	160.4560	39.0450
Wedge Side	0.025	19.7830	0.6310	19.1520	5.0310
	0.05	28.5470	1.2410	27.3060	7.2163
	0.25	81.0320	3.0400	77.9920	20.0383
	0.50	169.8300	8.3120	161.5180	38.0320

At the reference temperature of 20 °C, the surface deformations of prism under the gravity load are listed in Table 1. When the fluctuations of temperature ΔT are respectively 0.025, 0.05, 0.25, and 0.50 °C, the surface deformations are given in Table 2.

If the wavelength λ equals to 632.8 nm, the peak to valley (P-V) values of wave aberration, on the plane and wedge sides of prism, respectively are 0.01864λ and 0.01841λ, and correspondingly the root-mean square (RMS) values respectively are 0.00547λ and 0.00545λ. The above values, much less than Rayleigh criterion ($\leq \lambda/4$), show that the structure design is rational and feasible. In addition, the admissible stress 3.43×10^5 Pa of material K9 glass is much greater than the maximum equivalent stress of prism shown in Table 1.

With the temperature fluctuation of 0.05 °C, from Table 2, the P-V values of wave aberration of the plane and wedge sides respectively are 0.04411λ and 0.04315λ, and correspondingly the RMS values respectively are 0.01160λ and 0.01140λ, which are twice as much as those of prism under only the gravity load without temperature fluctuation. With the temperature fluctuation 0.50 °C, the P-V values of wave aberration on the plane and wedge sides of prism respectively are up to 0.2535λ and 0.2550λ, and the RMS values respectively are 0.06170λ and 0.06010λ, which attain or approach to Rayleigh criterion ($\leq \lambda/4$). Here the maximum equivalent stress of prism is about 3.0132×10^5 Pa, approaching the admissible stress of material.

From Table 2, by comparison, the strains of prism surface at temperature fluctuation of 0.50 °C, as well as the stresses, are appropriately eight times larger than those at temperature fluctuation of 0.05 °C, which is very serious. So the environment temperature must be well controlled. Meanwhile, the mounts of prism, according to the principle of thermal expansion, are best to use the material whose linear expansion factor is near to that of K9 glass, such as the indium steel (4J32,$\alpha = 5.5 \times 10^{-7}$/°C) and so on.

Figure 2 shows the corresponding relations of the strains and stresses to the temperature fluctuation, the increment of which is in proportion to the temperature increment from 0.025 to 0.50 °C. With the distortion data fitted through Zernike polynomial, the wave aberration map of prism surface without temperature fluctuation and with the temperature fluctuation of 0.50 °C can be visually described, as shown in Fig. 3. Because of the same constraints in two cases, the deformation currents of their plane sides are similar, but the deformation magnitude induced by temperature fluctuation in Fig. 3(b) already reaches micron magnitude, nearly eight times larger than the case in Fig. 3(a).

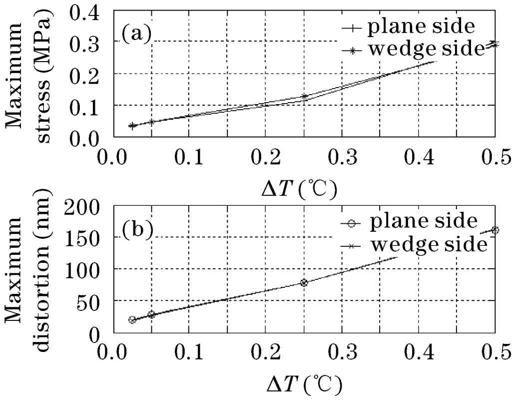

Fig. 2. Fitting curves of strains and stresses for temperature increment.

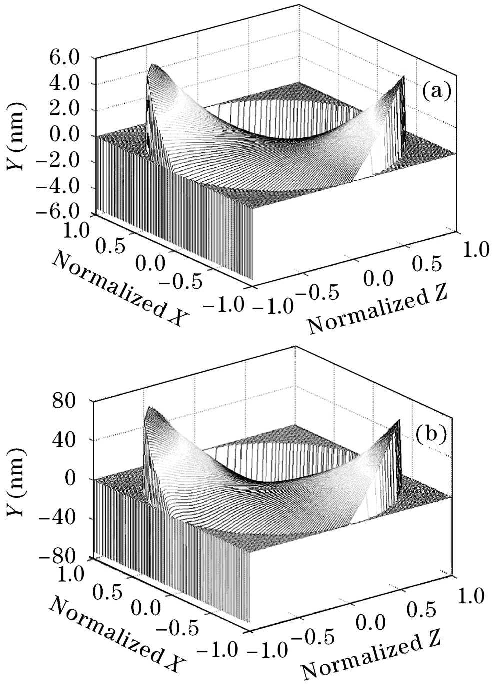

Fig. 3. Wavefront errors of plane side of prism. (a) Gravity load without temperature fluctuation; (b) thermal-structure coupling with temperature fluctuation of 0.50 °C.

Figure 4 shows the measured P-V and RMS values of

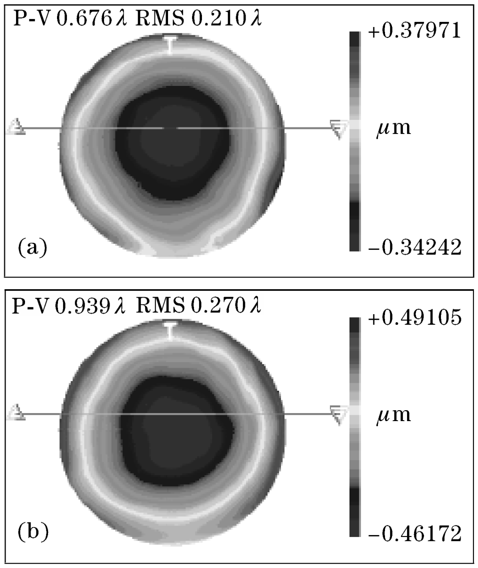

Fig. 4. Surface deformations measured by Zygo Mark interferometer at 20 (a) and 20.5 °C (b).

the plane side of prism at 20 and 20.5 °C with Zygo Mark interferometer in the temperature-controlled laboratory. The measured P-V and RMS values at 20.5 °C are respectively 0.263λ and 0.06λ larger than those at 20 °C, namely 166.4 nm and 37.9 nm. The errors of the P-V and RMS values between the measured values and the theoretical calculation values are within 10%, which strongly verifies that the above analysis is valid and correct.

In fact, the above analysis process is simplified and based on the rigid supports for the prism, but actually the supports for large optical components generally are elastic, therefore the stress and strain responses are less than some of the above analysis. The analysis on elastic supports is considered to be an elasto-plastic problem and will be detailedly studied in our following work. However, no matter what supports of optical components are, the analysis on the thermo-elastic distortion, as well as the test results of Zygo Mark interferometer, profoundly explain the impact of temperature fluctuation on the optical components. Therefore, the strict temperature-controlled measures for the practical application are to be considered.

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