Displacement Sensors Applied on Active Optics in Astronomical Telescope

Qi Yongjun[1], Zhang Zhenchao

Nanjing Institute of Astronomical Optics & Technology, National Astronomical Observatories, CAS, 188 Bancang Street, Nanjing City, 210042, P.R.China

ABSTRACT

Many types displacement sensors used in active optics in many astronomical telescopes over the world ware described and the measurement theory of different sensors were explained in this paper. Based on the displacement sensor's specification of LAMOST, a test bed to check it which used dual-frequency laser interferometer was established. Some main parameters affect on the measurement accuracy of the test bed such as temperature, vibration as well as some mechanism characteristics of fixing devices were analyzed in detail, and correspond solutions were adopted. According to theoretic analysis, rectification method was brought forward to compensate the errors of sensor cause by tip-tilt, thermal shift, non-linearity, and combined with the test results of some types sensors, their advantages and disadvantages was concluded. At last it forecasted the most appropriate displacement will be used in future active optics based on the discussion above and the developing trend of large telescope.

Keywords: displacement sensor, active optics, LAMOST, laser interferometer, rectification

1. INTRODUCTION

The active optics is developing quickly with the advancing of large aperture telescope, for example in KECK, HET and SALT, as well as LAMOST. As an important part of the active optics technology, many types' displacement sensors (or position sensor and edge sensor) were applied. The capacitive sensor was used in KECK and SALT, and inductive sensor was used in HET. LAMOST (Large Sky Area Multi-object Fiber Spectroscopic Telescope) is the unique telescope which use the thin mirror and segmented mirror technology simultaneously, so it has many rigorous requirements to sensors. There are many tasks of sensor were done to evaluate whether the sensor is suitable for LAMOST
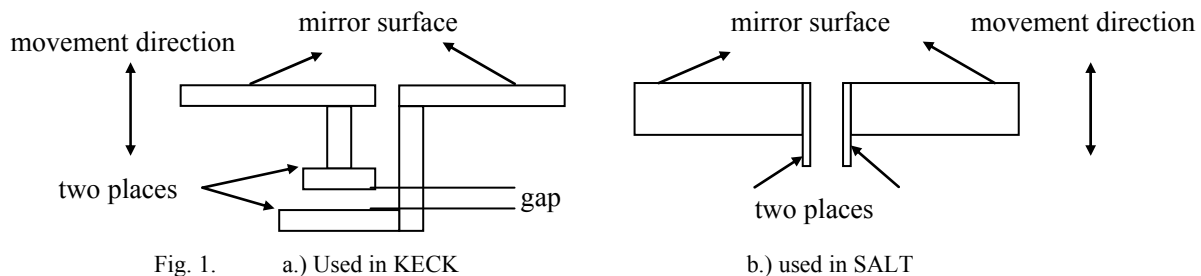
2. THE THEORY OF SENSORS

2.1 The theory of capacitive sensor

The capacity of two electrode plates is change with the gap between them or the effective projective area of them, the formula is,

$$C = \varepsilon_r \varepsilon_0 s / d \tag{1}$$

where ε_r is the relative dielectric constant, ε_0 is the permittivity of free space, s is the effective projective area and d is the gap.

Fig. 1.   a.) Used in KECK   b.) used in SALT

The diagram of capacitive sensor used in telescope is shown in figure 1.It shows the KECK use the change of gap to measure the displacement, while SALT use the change of area to do it. In the application on KECK, there is use the

differential technology to remove the noise caused by temperature, humidity, atmospheric disturbances and so on. In SALT, there are two other reference sensors to compensate the error caused by tip-tilt.

2.2 The theory of inductive sensor

The theory of inductive sensor is similitude to that of capacitive, but the change is inductance. That was used in HET, and is developing to be used in ELT.

2.3 Optical fiber sensors

The diagram of optical fiber sensor used in telescope is shown in figure 2.
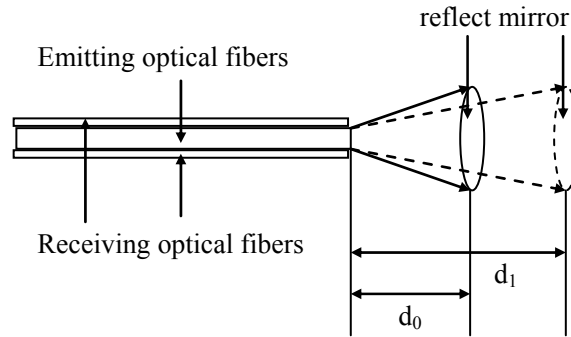

Fig. 2. Schematic drawing of optical fiber sensor

In this type sensor, the reflected light intensity is changed with the distance.

3. TEST BED FOR SENSORS

LAMOST need the measure range is not less than 2mm, accuracy is better than 50nm (RMS) and the operation temperature is from -25 to 25 degree, and the sensor is not heavier than 100g. It need a long measurement rang with high accuracy, to ensure the success of the whole project, a test bed was established.

3.1 The test bed

The real test bed is shown in figure 3. There is a dual-frequency laser interferometer, of which the resolution is 1.2nm; linearity accuracy is 0.2 ppm; measurement range is 40m; and the wavelength stability is 2×10^{-9}/hour and 2×10^{-8}/lifetime. The interferometer is fixed on the surface of an optical platform, the sensor and the reflect mirror are fixed on the staff of the actuator and keep the same movement driven by actuator.

The measurement formula of interferometer is,

$$L = N\lambda/2 \tag{2}$$

where L is displacement, N is wave number, λ is wavelength, then it drives from formula 2 and $\lambda=c/(n\times v)$ (v is the frequency) that,

$$\Delta L/L = \Delta\lambda/\lambda \tag{3}$$

where ΔL is the error.

The temperature T, air pressure P and the humidity affect on atmosphere refractive index is given by Edlen formula,

$$\frac{\Delta n}{n} = \left(-9.3\Delta T + \frac{3.6\Delta P}{133.324} - 0.0042\Delta f\right)\times10^{-7} \tag{4}$$

it shows the effects of temperature is great, so the test bed is put in a constant temperature room, the temperature stability is less than ±0.02 degree. This temperature stability can remove not only the disturbance of refractive index, but also the thermal deformation of mechanical devices in short distance measurement. To achieve that temperature stability, all thermal sources (include computer, motor driver of actuator, and human being) should be removed out of that room.

Each type of vibration can cause large error (maybe large than micron) within the measurement results, so there some vibration isolation methods should be applied:

a). around the ground base of the bed, dig a vibration isolation ditch;

b). use the spring stanchion to maintain the bed;

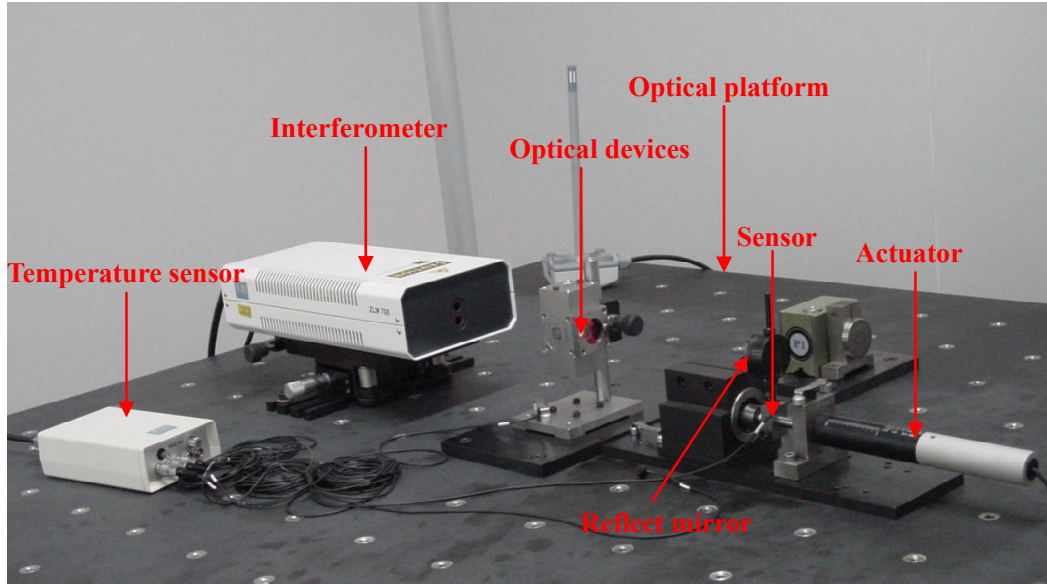c). use air float system within stanchion.

Fig.3. Real test bed

To get very high accuracy, it should use all methods above at the same time; the material of mechanical fixing devices had better is invar to get least error.

On this test bed, the capacitive, optical fiber, and grating sensor were tested. From the results, the capacitive sensor has high accuracy and large measurement range, its best accuracy is about 25nm in several tens microns range, the largest range is 5mm, but it is sensitive to tip, tilt, temperature and humidity; the optical fiber is not as good as capacitive sensor, the accuracy is about 50nm within several microns range, the largest range is 1.2mm; the accuracy of the grating sensor is the same as that of the capacitive sensor, the largest range is 10mm, but it is very expensive.

3.2 Rectification method to the tip-tilt in capacitive sensor

When the two circular plates of capacitive sensor is not parallel to each other, the capacity is given by,

$$c = \varepsilon_0 \varepsilon_r \cos\phi \int_0^R \int_0^{2\pi} \frac{rdrd\theta}{d - r\cos\theta\sin\phi} \qquad (5)$$

where ϕ is obliquity. Compare with formula 1, there is errors caused by tip-tilt. Analyzed by computer, the error with distance and obliquity is shown in figure 4.

It shows the maximum error is 700nm, extremely lower than the requirement of LAMOST. A polynomial fitting method is brought forward to compensate this error. The actual distance d_0 is the function of measurement value d_m in one certain obliquity ϕ, and is described as,

$$d_0 = \sum a_i d_m^i = a_0 + a_1 d_m + a_2 d_m^2 + a_3 d_m^3 + ... \qquad (6)$$

where a_i is polynomial coefficients, and change with different ϕ, it mean the polynomial coefficients is the function of obliquity, use the polynomial fitting method again, then formula 6 is expressed as,
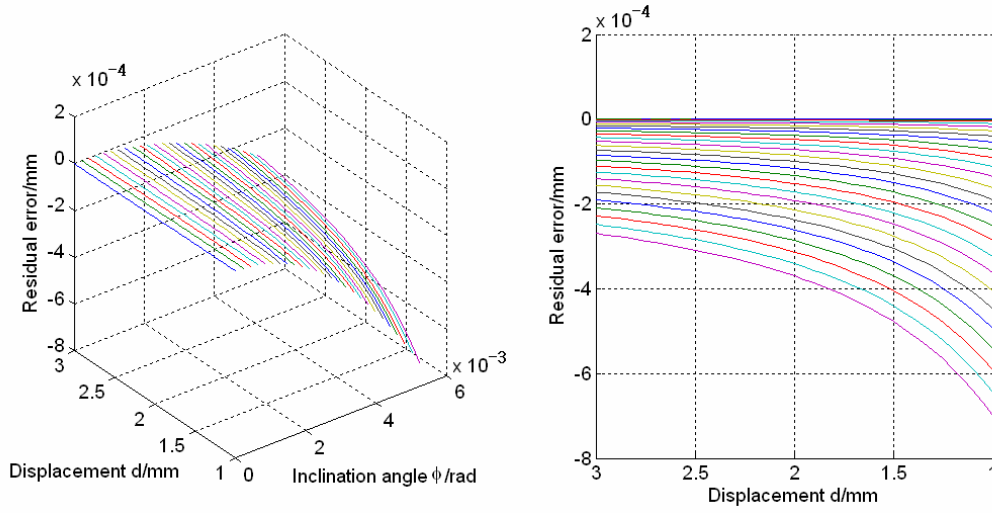
Fig.4. Tendency of absolute error

$$d_0 = \sum a_i(\phi)d_m^i = a_0(\phi) + a_1(\phi)d_m + a_2(\phi)d_m^2 + a_3(\phi)d_m^3 + ... \quad (7)$$

and
$$a_i = a_i(\phi) = \sum k_{ji}\phi^i = k_{0i} + k_{1i}\phi + k_{2i}\phi^2 + k_{3i}\phi^3 + ... \quad (8)$$

Simulated to different ranks of the polynomial by computer, it show the maximum error can be reduced to less than 2.5 nm through fitted by 2×4 order polynomial,

$$d_0 = \{\Phi\}^T[K]\{D_m\} = (1 \quad \phi \quad \phi^2)\begin{bmatrix} k_{00} & k_{01} & k_{02} & k_{03} & k_{04} \\ k_{10} & k_{11} & k_{12} & k_{13} & k_{14} \\ k_{20} & k_{21} & k_{22} & k_{23} & k_{24} \end{bmatrix}\begin{Bmatrix} 1 \\ d_m \\ d_m^2 \\ d_m^3 \\ d_m^4 \end{Bmatrix} \quad (9)$$

The matrix **K** can be valued by formula 1 and 5, and the result is shown in figure 5.
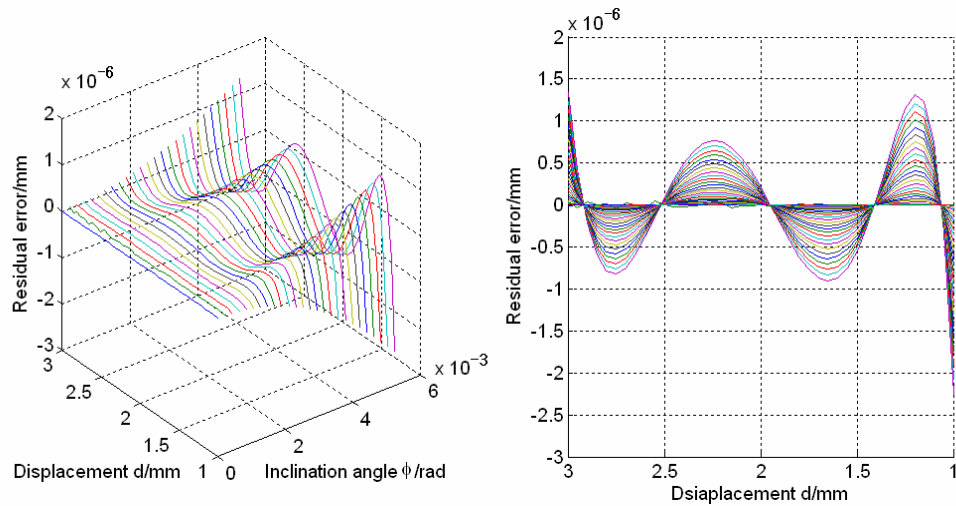

Fig.5. Fitted with 2×4 order polynomial (residual error<2.5 nm)

4. CONCLUSION

Several types of sensor were tested except inductive sensors, but which being suitable for LAMOST is developing. The capacitive sensor tested is heavy than expected and cannot ensure to be used in outdoor environment; the optical fiber sensor has small measurement range and lower accuracy, while the grating sensor is heavy and very expensive. But it is exciting that a kind of capacitive sensor is used in SALT successfully, and a kind of inductive sensor is developing to be used in ELT, their specification seems achieve the requirements of LAMOST. Future sensors used in telescope should have large measurement range, high accuracy, and should be independent of gap (that used in SALT), tip-tilt, rotate and all kind of environment factors, also should have small dimension and light weight.

REFERENCES

1.   NELSON J E, MAST T S, FABER S M, *The Design of the Keck Observatory and Telescope (Ten Meter Telescope)*, Keck Observatory Report, No. 90R, 1985.
2.   KRABBENDAM V L, *Development and performance of Hobby Eberly Telescope 11 meter segmented mirror*, Proceedings of SPIE - The International Society for Optical Engineering, 2002, vol.3352, 647-658
3.   CHANAN G, NELSON J E, et al, *Design Issues for the Active Control System of the California*, Proceedings of SPIE - The International Society for Optical Engineering, 2000: vol. 4004, 363-372.
4.   Yang Dehua and Qi Yongjun, *Structural error correction and simulation of capacitive displacement sensor for segmented mirrors*, Optics and Precision Engineering, vol.16 No.2, 173-178, 2006
5.   PADIN S, A differential, tilt-independent displacement sensor for the CELT mirror, http://tmt.ucolick.org/, August 2001.