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PRECISE ANGLE MONITOR BASED ON THE CONCEPT OF PENCIL-BEAM INTERFEROMETRY*

Shinan Qian and Peter Takacs
Brookhaven National Laboratory
Upton, NY 11973-5000

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Precise angle monitor based on the concept of pencil-beam interferometry

Shinan Qian and Peter Takacs
Brookhaven National Laboratory, Upton, NY 11973, USA

ABSTRACT

The precise angle monitoring is a very important metrology task for research, development and industrials applications. Autocollimator is one of the most powerful and widely applied instruments for small angle monitoring, which is based on the principle of geometric optics. In this paper we introduce a new precise angle monitoring system, Pencil-beam Angle Monitor (PAM), base on pencil beam interferometry. It's principle of operation is a combination of physical and geometrical optics. The angle calculation method is similar to the autocollimator. However, the autocollimator creates a cross image but the precise pencil-beam angle monitoring system produces an interference fringe on the focal plane. The advantages of the PAM are: high angular sensitivity, long-term stability character making angle monitoring over long time periods possible, high measurement accuracy in the order of sub-microradian, simultaneous measurement ability in two perpendicular directions or on two different objects, dynamic measurement possibility, insensitive to the vibration and air turbulence, automatic display, storage and analysis by use of the computer, small beam diameter making the alignment extremely easy and longer test distance. Some test examples are presented.

Keywords: angle measurement, pencil-beam interferometry, precise, LTP, autocollimator

1. INTRODUCTION

Precise angle monitoring is a very important task for research, development and industrial application. Any object has 6 degrees of freedom, 3 are in linear directions and the other 3 are in angle directions. The accuracy determines the quality of the task. There are a lot of instruments or tools are able to test and to set the object angle to a proper position. For example, goniometer, theodolite, level and so on are for the measurement of large angle up to 360 degrees. On the other hand, angle gauge, polygon, autocollimator, small angle generator, bubble level and so on are for the test of small or relative angles.

The precise Pencil-beam Angle Monitoring, (PAM), that we describe in this paper, belongs to the category of small angle measurement. In this category, the autocollimator is one of the most important and widely applied instruments. In a long period development, the autocollimator have had visual version, electronic version, TV version and TV-computer version. Its accuracy/resolution can be 0.01 arc second in a small angle range or several seconds for a large measurement range.

The principle of the autocollimator is very simple: a reticle acting as an object, positioned at the focal plane of objective and illuminated by a light source, becomes bunches of parallel lights out of the objective. A plane mirror reflects back the beam then an image of the reticle is generated on the focal plane of the objective. When the mirror is rotated the image will move laterally. The tangent of angle deviation is equal to that of image displacement divided by double the focal length according to the reflecting principle. The longer the focal length, the higher the accuracy/resolution will be in principle. If the mirror is attached to an object, the object angle displacement can be known clearly. The visual version of autocollimator is simple but is less accurate, the TV version is more convenient than the visual, the electronic version improves the accuracy by use of a sensitive optic-electronic method, and the TV-computer version uses the software to improve the accuracy and is easy to operate. However, the angle deviation is determined by identifying the reticle image position.

The autocollimator can be used to test angle of optical components like parallel plate, edge, prism, to test angle displacement of gauges and mechanics including straightness and flatness of mechanical slide, table, to align the precise units or component for printer, robotics arms and so on during precise assembling, and to monitor angle stable and so on.

The restrictions to use autocollimator are:

a) The mirror surface, to reflect beam back to the autocollimator, must be larger, for example, at least 10 or 20 mm. This will reduce its application range on the compact and precise load-sensitive system
b) The mirror surface must be very flat in order not to blur the reticle image and not to offset the image position which will decrease the test accuracy significantly
c) The test distance is restricted by weak light source and larger aperture
d) It is not easy to reach high resolution and accuracy
e) The test speed is generally low
f) It is sensitive to the air turbulence
g) Only one object can be tested at a time

However, relying on the different concept of the pencil beam interferometry, the Pencil-beam Angle Monitor overcomes most disadvantages of the autocollimator in addition to similar applications. It has higher sensitivity, higher accuracy, longer testing distance, small target surface up to 2 mm, the mirror surface needs not very flat, very stable characteristic, not sensitive to the air turbulence and there are two monitoring beams can be used for the test on two objects simultaneously. So it should have various and wide applications. Of course, certain disadvantages are involved.

2. OPTICAL PRINCIPLE OF THE PRECISE PENCIL-BEAM ANGLE MONITOR (PAM)

2.1. Main optical system:

The PAM is based on the concept of pencil-beam interferometry introduced by K. von Bieren [1, 2] in 1982. It is a directly angle measurement method. This principle has made the Long Trace Profiler (LTP), an instrument to measure slope error of large mirrors with the surface shape from plane to aspheres, very precise and successful[3-9]. The PAM obtains the benefits from LTP improvements.

The optical schematic of the PAM is shown in Fig. 1. A Diode laser (DL) is used as the light source, which is collimated by a lens (CL). This single collimated beam of about 1 mm size is converted to a set of two parallel beams by an equal optical path system (EOPS) including RP1, RP2 and BS[3, 4] which ensures that there will be no influence on the test result caused by laser frequency shift resulting in the possible use of unstable laser. The separation of two beams is about 1 mm, so only 2 mm beam spot is as the monitoring beam for the PAM. The beam set passes through a polarizing beam splitter (PBS) and becomes two sets monitoring beams perpendicularly or in parallel by reflecting from a right angle prism (RP3). Each set includes two parallel beams so it is possible to test two angular displacements individually but simultaneously, or they can be used in combination to create new measurement methods. When the measurement accuracy requirement is extremely high one of the beam sets can be used as a correction beam to compensate the smaller thermal impact . These two beam sets are reflected by small plane mirrors (M1, M2) attached to the object under test or just reflected by the object itself if there is small polished surface on it. The reflected beam sets are returned to the PBS and sent to the Fourier transform (FT) lens, which focuses the two beam sets to its focal plane. The two overlapped beams of each set create a clear interference fringe (IF). Because of the diffraction, the beam spot of 1mm will enlarge to 1.6 mm of interfering spot at the focal plane according to the Airy disk calculation [10] as equation (1)

$$\text{Airy disk diameter of diffraction spot} = 2 * (1.22\,\lambda) * f / D \qquad (1)$$

where D is aperture diameter of the beam spot of 1mm on the FT lens and f is the focal length of the FT lens, 1250 mm. So the interfering fringe is restricted in a 1.6 mm spot.

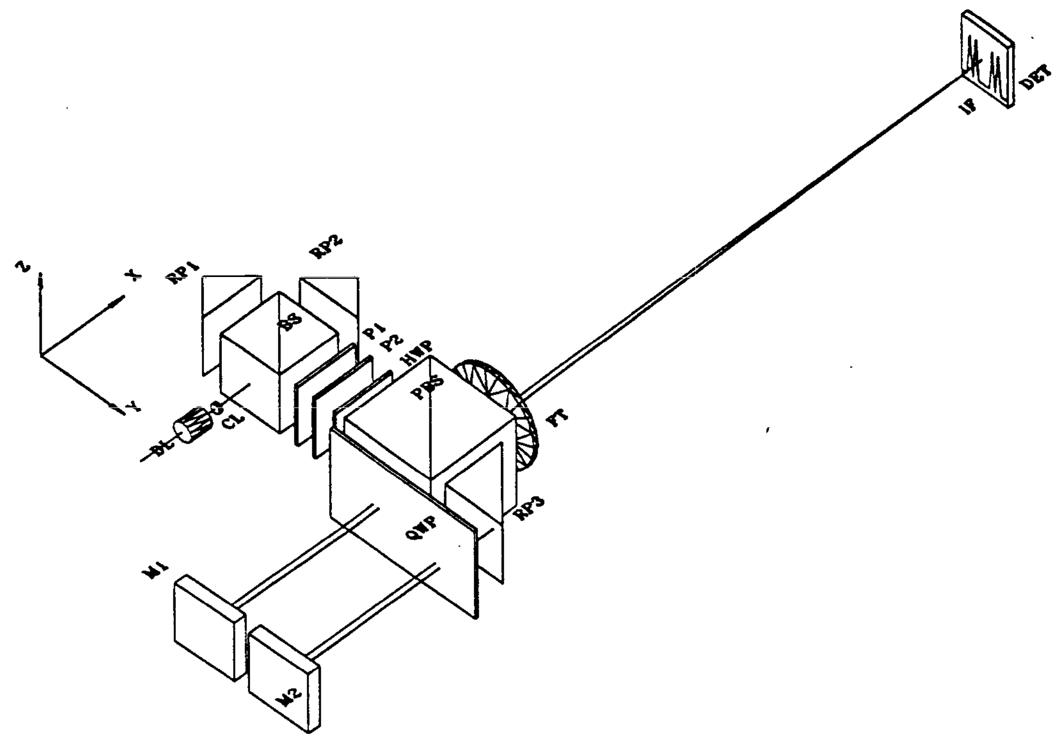

Fig.1 Optical schematic of Pencil-beam Angle Monitor

If there are angle displacements of M1 and M2 the fringes will move on the focal plane laterally. An linear array detector (DET) is just located at the focal plane of the FT lens in order to detect the fringe movement. The quarter wave plates (QWP) are used for rotating polarization directions in order to drive two beams sets to the FT lens. The polarizer 1 (P1) is for obtain a better polarizing beam, polarizer 2 (P2) can be rotated for adjusting intensity of test beams and half-wave plate (HWP) can be rotated either for balancing two beam sets. Of course, a He-Ne laser coupled with optical fiber used for the LTP. can be used as the light source either for the PAM but it increases the size significantly.

The mathematical relation between angle displacement and linear displacement is similar to that of autocollimator. The rotating angle α of the mirror will be determined by the tangent of the angle

$$\tan(\alpha) = d / 2f \qquad (2)$$

or if $f >> d$, reduces to

$$\alpha = d / 2f \qquad (3)$$

where d is the fringe movement in the focal plane (Fig. 2).

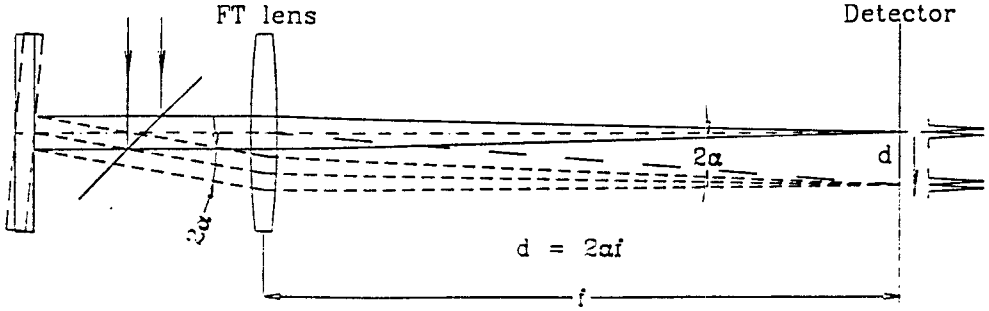

Fig. 2 Relationship between angular displacement and linear movement of interference fringe

However, the main differences of the PAM from autocollimator is to use interference fringe of very small beam spots to identify reflecting angle. This Characteristic creates significant advantages of the PAM comparing to the autocollimator.

2.2. Principle of testing two perpendicular angle deviations at the same time:

As described in the previous paragraph (Fig. 1) there are two beams which can be used to test two objects. Because the detector is a linear array, it can only detect the fringe movement along the line direction Y when M1 is rotated around axis Z. The angle deviation produced by rotating M2 around axis Y will only cause vertical movement (Z direction) which is not detectable by the linear detector. In order to measure the angle deviation there are three requirements for the PAM: the first is that the two output beam spots should be lined up in the angle deviation plane; the second is the interference fringe should be perpendicular to the detector line (Y); and the third is that the fringe movement should be parallel to the detector line. A Dove prism is used to fulfill these requirements. The vertical scan version of the LTP uses the Dove prism to rotate the beam spot by 90 degrees for testing circularity error of the X-ray telescope mirror[11]. As shown in Fig. 3, in the PAM case the Dove prism is placed in front of the PAS rotated by 45 degrees relative to the normal position so that the output beam spot becomes vertical. When the mirror M2 rotated around the Y axis, the beam spots move on vertical direction before passing Dove prism, but after passing through the Dove prism, the beam spots become horizontal and move horizontally according to the Dove prism character. In this way two angle deviations in perpendicular directions can be tested successful at the same time. Fig. 3 shows the beam spots sets direction and their moving direction of out and in.

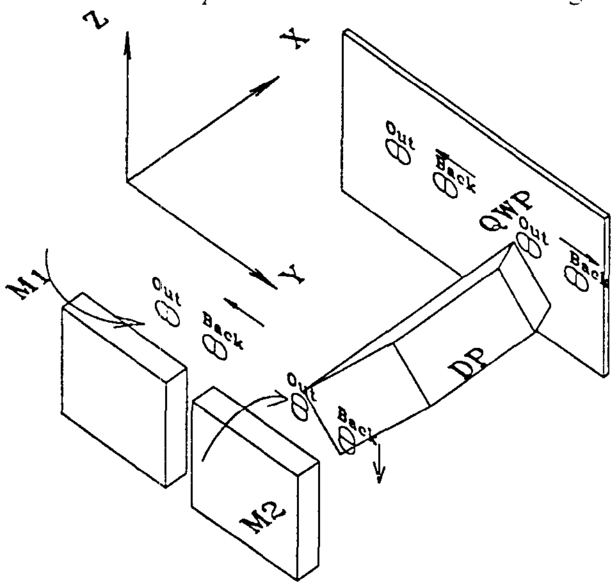

Fig. 3 Principle of testing two perpendicular angle deviations at the same time by positioning the Dove prism in 45 degrees

The data acquisition from the detector is done by frame grabber and then saved to the computer automatically. A laptop is equipped for the PAM. The software analyzes test results at once and plotted on the computer screen in time.

3. HIGH ANGULAR SENSITIVITY AND RESOLUTION

The PAM has very high angular sensitivity of at least 0.01arc second because we use a curve-fitting method to find fringe position at its precise minimum. If we use an FT lens with f = 1250 mm and a detector with the pixel distance of 25 microns, the resolving power of one pixel is only 2 arc seconds. By use of mathematical method to fit the tested fringe curve, a closest theoretical equation of the 2nd order polynomial curve can obtain. Via careful calculation, the peak or valley position of the fringe fitting equation can be located very accurately. According to the experience of the LTP, in this way the angular sensitivity can increase in a ratio of 200:1. It means a resolution of 0.01 arc second (0.05 μrad) or 0.125 μm fringe movement can be easily recognized. If the detector pixel size is reduced then the FT lens focal length could be also shortened, making the PAM smaller. However, if the noise level of the detector improves the resolution could be higher.

Practical examples of this achievable resolution of the PAM are presented in Fig. 4. Fig. 4a) is the tested slope curve of a stability scan and Fig. 4b) is the scanned slope profile of a plane mirror of 200 mm long.

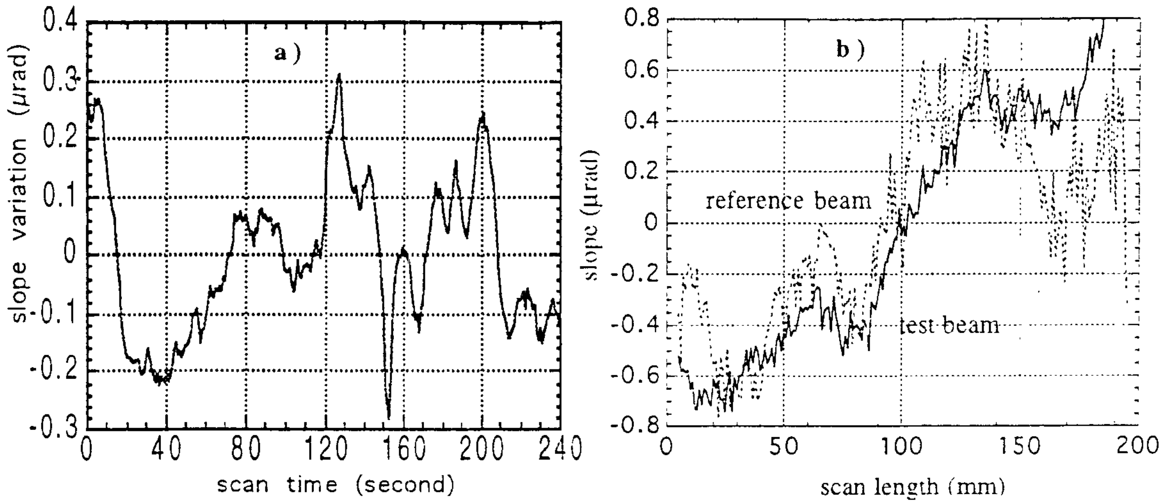

Fig. 4 Practical slopes tested by LTP indicate the pencil-beam interferomentry method used by PAM has a resolution of better than 0.05 micron radian (0.01")
a) a stability scan b) a measurement on a plane mirror

4. STABLE CHARACTERISTIC

One of very attractive features for this angle monitoring system is great stability so it is able to monitor sub-microradian deviation of object systems or units over periods of days. For example, to measure sub-μrad angular stability and deviation of platform, the mechanical structure, optical components, thermal impact on objects to be used in stable instruments and so on.

For the comparison, the standard LTP optical system does not have sufficient long-term stability to be considered for use as a long-term stable angular monitor in sub-μrad stability level, because it can achieve about 1 μrad rms in a ±0.1 degree environment over 15 hours, and also it must apply the reference beam correction. Reference beam subtraction mainly (but not entirely) corrects errors produced by mechanical relaxation, force distortion and thermal expansion. However, the PAM produces very stable probe beams without the need of reference subtraction in short-term or long term. Then we can measure two angular factors together at the same time on two output beam sets. In addition to that described above, the PAM requires to operated in a worse temperature environment, for example, 0.5 - 1 degree, but still to posses high accuracy.

The EOPS and the laser sets of the PAM are fixed and clamped rigidly into a sealed cube, incorporating with the symmetric structure design to reduce the thermal impact and with the use of low expansion material. With these improvements the PAM stability increase significantly.

We tested the PAM stability in following conditions: use plane mirror M1 to reflect beam back to the PAM. M1 is fixed on the flexible mount produced by Newport Inc.. M1 is close to the PAM, temperature variation in the PAM is about 0.5 degree. The stability test results show 0.25 μrad rms (0.05 arc second rms) or 1 microradian peak to valley (0.2 arc second, P-V) in 24 hours (Fig. 5). This is good enough to use as an excellent angular monitor system.

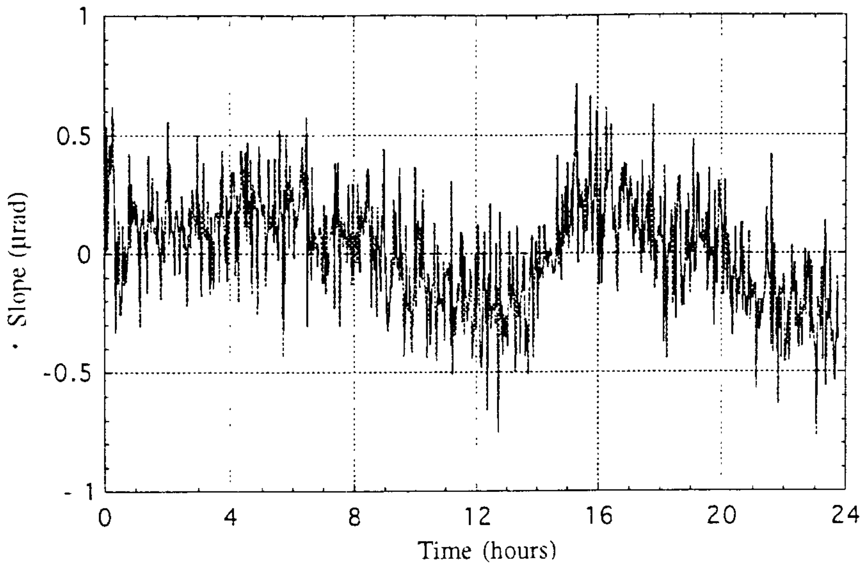

Fig. 5 Stability of the PAM, only 0.25 μrad (0.05 arc second) rms slope shift in 24 hours

5. POSSIBLE HIGH MEASUREMENT ACCURACY

High stability and sensitivity are the base of approaching high measurement accuracy. Of course, they are not equal to the accuracy. However, the instrument accuracy in very small test range is basically determined by the instrument stability and sensitivity because many error sources in this small test range are negligible. For example, assuming the FT lens spherical aberration is 1mm in axial direction, it creates maximum 10 microns error on detector when the beam is incident on the FT lens edge at 12.5 mm, it is equal to 4 μrad if the FT focal length is 1250 mm. If the beam is incident at a distance closer to the FT lens center the aberration error will be smaller. If the distance between the FT lens and M1 (Fig. 1) is about 100 mm, while it is monitoring 30" angular displacement, the beam spot will move laterally about only 0.00015 * 100 * 2 * 1000 = 30 μm. To simply estimate the error created by the FT lens aberration could be considered as a portion of the maximum error: 4 μrad * (30 μm /12500 μm) = 0.01 μrad. It is negligible. The errors produced by detector focal position misplacing and by imperfect optical surface in small angle range have the similar small portion of errors like aberration, can be negligible either.

In the larger test range the accuracy will be influenced by a lot of facts. We have not tested the possibly highest accuracy of the PAM yet. However, due to the similar FT lens system for determining the angle value as autocollimator objective, the better curve fitting technology of PAM and the LTP experience, we can estimate the PAM has at least the same accuracy as that of autocollimator or better. Summarizing the accuracy information of autocollimators they are about: within the range of 10-30" the accuracy is about +/- 0.01"-0.02" within the range of 1000"-2000" the accuracy is about +/- 0.1"-0.2".

6. COMPARISON BETWEEN USING SINGLE BEAM AND USING DOUBLE BEAMS

In principle, we can use single beam as monitoring spot instead of using double beams to create interference fringe. It seems the equal optical path system (EOPS) (Fig.1) could be replaced. However, the profile of the interference fringe is much sharp than the intensity profile of single beam spot and it can be detected much more precisely[12]. On the other hand, the interference fringe profile is much reliable and accurate because fringe is formed by all diffraction rays of two beam spots in entire aperture. So the fringe position is an average. In the contrary, for the single beam spot the intensity profile is influenced by local events like different reflectivity, material uniformity, roughness, dusts and so on, these will change the profile maximum position and will create errors. Fig. 6 is the comparison experience of using single beam and double interference beams. It shows the single beam detection is rough.

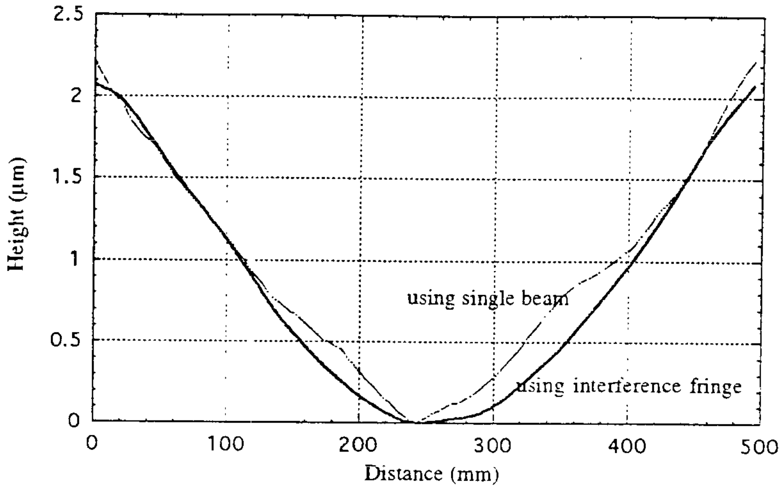

Fig. 6 Flatness tested by using different probe beams: two interference beams and single beam by blocking one beam of RP1 or RP2. The double beam is much smooth

7. SIMULTANEOUSLY TWO PERPENDICULAR DIRECTION ANGLES TEST BY USE OF THE PAM: STRAIGHTNESS TEST

As described previously the PAM has very stable character so it is good to use two beam sets to test two angular objects.

Following is the measurement example of yaw and pitch of an air bearing slide in order to show the reliability. We use the configuration of Fig. 3, a Dove prism has to be put in front of the PAM main system. The M1 is for the yaw test and the M2 is for the pitch test. M1 and M2 set on the carriage of the air bearing in the dimensions of 63 (width) x 31 (height) x 700 (long) mm. It is a ceramic bar. The moving weight of the carriage, mirrors and mounts is about 1.5 Kg. The scan begins at one end so the scan center does not coincide with the slide center.

Fig. 7 shows the measurement results. a) is tested only with the carriage, mirrors and mounts, b) is tested with an extra load of about 0.8 Kg. The yaw is smaller and when the load increases the yaw value reduces. On the other hand the pitch test result show the large ceramic distortion clearly. When the load increases the segment increases either. The maximum distortion position is located about 250 mm from the beginning which is center of the bar.

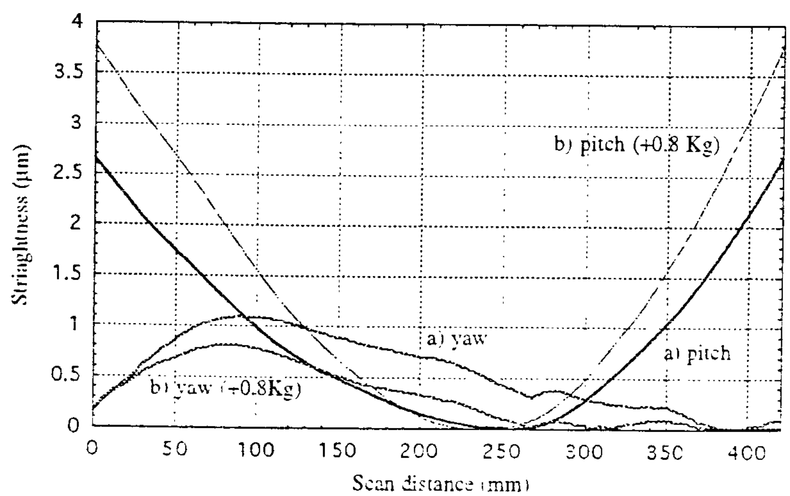

Fig. 7 Pitch and yaw measurement of an air bearing slide tested at the same time. Set a) is tested with a normal load and set b) is tested with an extra load of 0.8 Kg

8. OTHER ADVANTAGES OF THE PAM

In addition to the advantages of very stable character, high sensitivity, high accuracy and so on described above, the PAM has several other advantages as following:

a) The light beam size of the PAM is about 2 mm sent from a diode laser or He-Ne laser with the power about 5 - 20 mw. Due to the power, small divergence and small beam size it is good enough to measure the anti-reflecting coating surface. The small monitoring beam spot is very important for testing today's compact systems.

b) The strong and small beam makes very easy to align in seconds. It is much convenient than autocollimator especially when it is operated over a long distance.

c) The PAM is possible to test the angular deviation when the beams are reflected from a not flat surface even a sphere mirror of larger radius of curvature. Of course, when non-flat surface is used to reflect beam, the lateral movement of this surface should not exist in order to reduce the error. In contrast, the autocollimator has to use a mirror with the flatness of better than $\lambda/2$, otherwise it will blur the image and reduce the accuracy or will even make test impossible.

d) Dynamic measurement ability: Due to the application of line detector the test speed can be much higher than that using array detector. An array detector can reach 20-30 frames each second with the Analog to Digital Converter (ADC) of 12 bit, for a line detector it is no problem to reach at least 100 lines per second. It is good for dynamic angular monitoring with the PAM. For example, to test tilts and vertical movement of the rotary carriage during the CD ROM driver running. Recent prototype data acquisition speed of the PAM is about 20 points per second with the common 16 bit ADC.

e) With the computer aid the real-time display of slope and height curves, the data storage, plotting are available and the precise analyzing are easy.

f) By combining with two output test beam sets of the PAM one can develop different kind of configurations to suit different test purposes. Following is a very brief description as an example to test polygon angles with great accuracy by use of single PAM: let one beam set of the PAM incident to one surface of the polygon under test about perpendicularly and let second beam set towards to the adjacent surface about perpendicularly either via a mirror M3 (Fig. 8). These two fixed beam directions is used as a comparison angle, then rotate the polygon to compare every its angle step by step in order to read the angle differences $\delta\alpha$ from the PAM. This can be done automatically if a computerized rotary stage is used to drive the polygon. Assuming the angle differences of readings are $\delta\alpha$ i ($\delta\alpha 1$, $\delta\alpha 2$,... $\delta\alpha n$) (of course, $\delta\alpha 1 = 0$), then the real angle errors of each polygon angle will be: real $\delta\alpha$ (i) = $\delta\alpha$ i - $(\delta\alpha 1 + \delta\alpha 2 + \ldots + \delta\alpha n) / n$ because the sum of the errors should be zero. With one PAM the polygon angle measurement accuracy can reach 0.01 arc second because for each beam set the angle deviation range is very small. In the case of using autocollimator, two precise autocollimators are probably necessary.

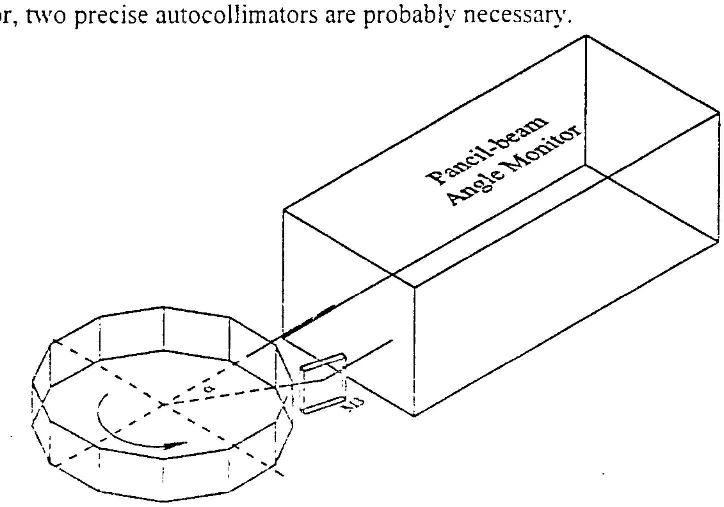

Fig. 8 Polygon angle test by use of Pencil-beam Angle Monitor: two output beam sets of the PAM incident to two adjacent surfaces with an angle of about 360 degrees/n, where n is the polygon number

g) Because the PAM interference fringe is based on the optical path difference of two beams which are very closed together so air-turbulence and vibration impact of two beams are closer resulting in the less influence to the test result.

However, the disadvantage of the PAM is that it is hard to test two closer fringes, because they partially overlap and interfere each other, for example, in the case of prism angle test.

9. CONCLUSION

Pencil beam Angle Monitor is a new precise instrument base on pencil-beam interferometry. The specific characteristics are: high angular sensitivity of <0.01 arc second, high stability of 0.05 arc second rms in 24 hours, possible high measurement accuracy in the order of 0.01 arc second in small range, simultaneous measurements in two perpendicular directions or on two different objects, high measurement speed, insensitive to the vibration and air turbulence, small pointing beam of about 2 mm, and automatic display, storage and analyzing by use of the computer.

The same applications of the PAM as autocollimator are: straightness and flatness test of slides and plane plates, relatively angle test of optical components, angle displacement measurement of mechanical components and units, precise angle stability monitoring of platforms, alignment of optics, mechanics and assemble units, alignments of synchrotron radiation beam lines and monochrometers. The different applications comparing to the autocollimator are: test availability on small surface, long period angle stability monitoring, possible test in long distance, possible to test two angle events at the same time and dynamic measurement.

Further works of the PAM are: to estimate the potentially highest accuracy, to find new applications, to develop a precise, stable, convenient instrument and so on.

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