

THE NON-CONTACT MEASUREMENT OF ULTRA-PRECISION HEMISPHERE

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Abstract: As the high rotating speed of air bearing in astronautic gyro, the geometrical parameters (radius, sphericity) of its hemispherical contour must be with ultrahigh accuracy in the order of sub-micrometer. The non-contact pneumatic measurement technique is applied. In this paper, a new type of “air-pin” so-called pneumatic electronic sensor developed by the authors is introduced first. This sensor consists of fine nozzle of less than 0.15 mm in diameter, and its measurement resolution is 0.01 μm, measurement repeatability is within ± 0.05 μm. The spherical pneumatic gauge with multi-nozzles and sensors is used in a computer-based testing system to measure radius and sphericity of hemispherical surface. The measurement uncertainty of this system is less than ± 0.5 μm. It has been used in a project of measuring hemispherical surface of an air bearing of astronautic gyro. It can also be used to measure different three dimension contour in precision engineering

Keywords: measurement, non-contact, sphere

1 INTRODUCTION

The technique of measuring small different size of machine parts by causing them to influence the air pressure or flow rate is generally known as “pneumatic measurement technique”. The principles can be explained by reference to Fig. 1.

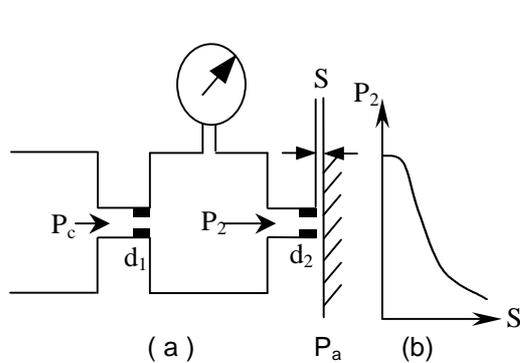


Figure 1. Pneumatic measurement principles

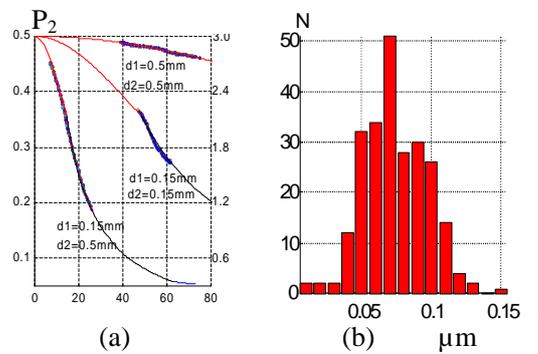


Figure 2. Experimental results

The air at constant high pressure P_c flows from supply to atmosphere P_a through restricting nozzle d_1 and measuring nozzle d_2 (Fig. 1 (a)). The diameter d_1 is constant. The variation in separation S between measuring nozzle d_2 and the plate of work piece measured will cause an alteration in back-pressure P_2 in the chamber. This pressure P_2 can be measured with a gauge or a pneumatic-electronic sensor with suitable sensitivity. According to the functional relationship between pressure P_2 and separation S , $S = f(P_2)$ as shown in Fig. 1 (b), we can measure the variation of the size on the work piece with very high accuracy.

Based on the Bernoulli equation, continuity equation and gas state equation, the relationship between P_2 and S , $P_2 = f(S)$, can be obtained (Fig. 1 (b)) [1,2,3].

When $P_2/P_c = 0.528$ and $P_a/P_2 = 0.528$,

$$P_2 = P_c \left[\frac{0.25c_1 d_1^2}{c_2 d_2 S} \right] \quad (1)$$

When $P_2/P_c > 0.528$ and $P_a/P_2 < 0.528$,

$$P_2 = P_c \left[0.5 + 0.5 \left(1 + 4 \frac{A^2}{B_1^2} S^2 \right)^{\frac{k}{1-k}} \right] \quad (2)$$

where c_1, c_2 —flow coefficients of nozzles d_1, d_2
 k —specific entropy, $k=1.41$ for air

$$A = \frac{c_2 d_2}{0.25 c_1 d_1^2} ; B_1 = \frac{\sqrt{(k+1)/(k-1)}}{k \sqrt{2/(k+1)}} \quad (3)$$

Although the function $P_2=f(S)$ is nonlinear, we can choose a segment on the function curve as a linear measurement range in which the measurement sensitivity is constant approximately. For the traditional back-pressure pneumatic sensor, usually $P_c=0.1$ MPa~ 0.2 MPa, $d_1=1$ mm, $d_2=1.5$ mm ~ 2 mm, linear measurement range= 10 μ m ~ 200 μ m, and measurement accuracy is about 0.1 μ m ~ 1 μ m. According to this principle, some non-contact pneumatic measurement systems have been used for industry inspection of dimensions on the work pieces.[1,2,3,4]

2 AIR-PIN PNEUMATIC SENSOR

According to the function $P_2=f(S)$, increasing the supply pressure P_c and decreasing the diameter of d_1 , the measurement range of sensor will be decreased, but the sensitivity will be raised. So that, we developed a new pneumatic sensor with fine jet of 0.1 mm ~ 0.2 mm in diameter d_1 and d_2 , supplied high-pressure air of $P_c=0.4$ Mpa ~ 0.6 MPa. In this condition of pneumatic critical state (i.e. airflow velocity reaches sonic velocity) in the sensor, the sensitivity and accuracy of the sensor will be raised. As the output air stream from measuring nozzle likes a fine pin, so we call this sensor “air pin” pneumatic sensor.

In the experiment plan, tests are performed with different d_1, d_2 as well as P_c . Some typical experimental curves $P_2=f(S)$ are shown in Fig. 2 (a). Experiments in 200 times of repeatable operations also show that the measurement repeatability is less than ± 0.05 μ m with resolution of 0.01 μ m in the linear range (Fig. 2 (b)), and the stability in 12 hours is less than 0.06 μ m.

Comparing with the traditional pneumatic sensor, the air pin sensors have some different performance from the theoretical equation of aerodynamics. The main reason is that, we thought, the flow coefficient c_2 is varied when the separation S extents from zero to measuring range. Especially when S is less than 10 μ m, the roughness on the surfaces of nozzle and work piece measured has a lot effect on the turbulent airflow and c_2 . According to the Navier-Stokes equation and continuity equation, the flow function for the axial-symmetric flow (Fig. 3a) can be deduced to calculate the flow rate and the thickness of the boundary layer [5,6,7],

$$Z = -z \nu F(z)/u_z \quad (4)$$

where: Z – thickness of the boundary layer

$z, F(z)$ – state variable and its function relative to air dynamic viscosity coefficient ν

u_z – flow velocity in the direction z of nozzle axis.

For example, when $P_a/P_2 < 0.528$, u_z is about sonic velocity, we can estimate the thickness of the boundary layer, $Z=0.36$ μ m. Considering the possible roughness $R_z=0.8$ μ m ~ 1.6 μ m on the fine machining surface of the nozzle and work pieces, the thickness of the boundary layer will be increased to more than 1 μ m in practice. It means that there is a remarkable percentage of the thickness of boundary layer in the separation S (Fig. 3b). In this case of turbulent flow, the flow resistance will enhance and coefficient c_2 will be smaller than the usual and the nonlinear in the function will enhance. Therefore, we suggest that the roughness on the surface measured would be $R_z < 0.32$ μ m.

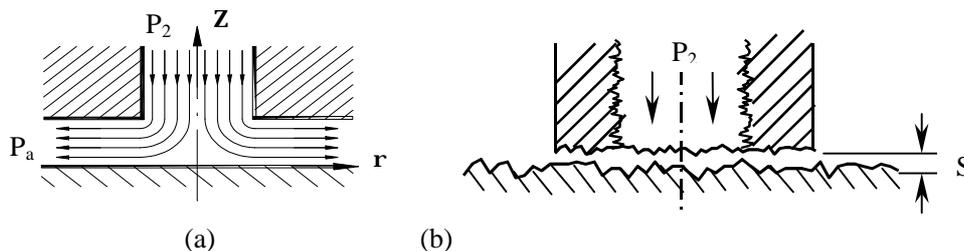


Figure 3. Axial-symmetric flow in the nozzle

3 MEASUREMENT OF HEMISPHERE

The air pin pneumatic sensor mentioned above has been applied to an inspection system for measuring radius and form error of the ultra precision hemisphere contour of air bearing.

As the high rotating speed of the air bearing in gyro, the radius and sphericity must have ultra accuracy. Some laser interferometers (e.g. Zygo Laser Interferometric Non-contact Profiler System) can be used to determine the spherical form error in the accuracy of $0.1 \mu\text{m} \sim 0.01 \mu\text{m}$, but limited in an area of 30%~40% of the hemispherical surface. Also it can not be used to measure the actual radius of the spherical surface.

3.1 Design of air gauge

We designed a spherical gauge with multi-nozzle (Fig. 4) to measure the dimensions of several points on the sphere contour, and then estimate the radius and the sphericity according to the minimum zone estimate method [8]. With the multi-point air gauge, we can test the whole surface of the hemisphere. Another advantage, comparing with the laser interferometer, is that the pneumatic measuring condition is more similar to the working condition in the air bearing of gyro. So the estimating results can characterize the working performance of the gyro more actually.

According to the optimal design method, six points for measuring nozzles are scattered evenly on the surface of air gauge.

No.	1	2	3	4	5	6
Longitudinal angle	0°	60°	120°	180°	240°	300°
Latitudinal angle	75°	40°	60°	75°	40°	60°

3.2 Error analysis

Eccentricity between air gauge and the work piece measured will cause a few measurement errors. In our system, when the measurement uncertainty of each air nozzle is $3S \pm 0.3 \mu\text{m}$ and eccentricity is less than $15 \mu\text{m}$, 500 times of simulation test have been made and the test results shown that the error was less than our design specification (Fig. 5).

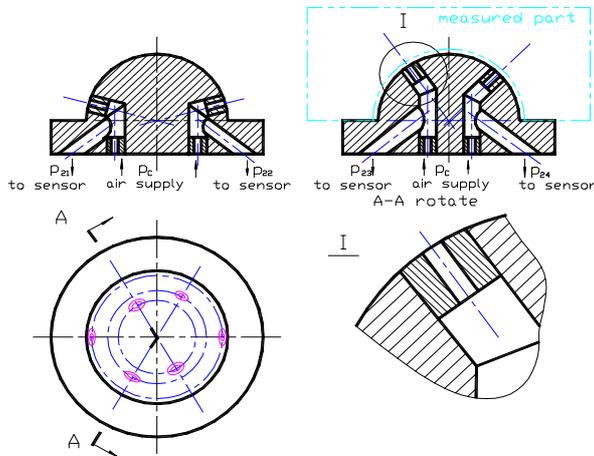


Figure 4. Pneumatic gauge

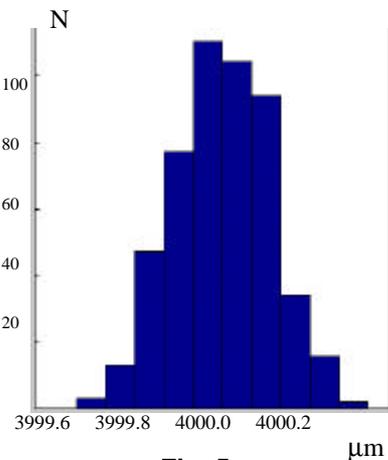


Fig. 5

The errors of longitudinal angles and the latitudinal angles of air nozzles have to be limited. The errors of diameter and length of every nozzle will cause the difference among the pneumatic performances of six nozzles significantly. We found, in the experiments of six nozzles of $d_1=d_2=0.15 \text{ mm}$, the maximum difference in measuring sensitivity K would be $(K_{\text{max}}-K_{\text{min}})=0.8 K_{\text{min}}$. That is not allowed in our precision measurement. So, the uniformity of the six pneumatic performances should be

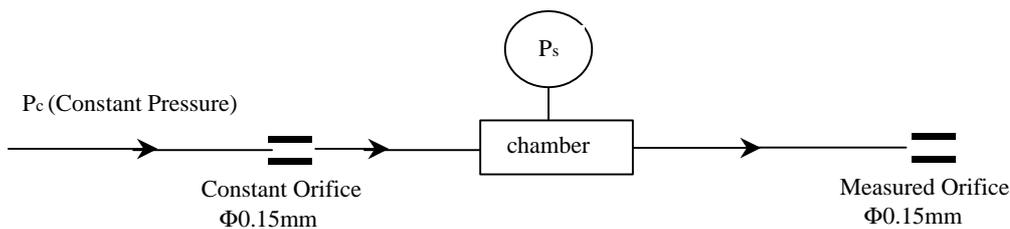


Figure 6. Schematic diagram of uniformity test

tested. Figure 6 is the schematic diagram of uniformity test for the different nozzles.

As decreasing the system errors, a standard ball has been used for calibrating the air gauge. Then, some hemispheres are measured with our air gauge. Test results are shown as Table 1.

Table 1.

No	calibrated hemisphere data (μm)		measured results (μm)	
	radius	sphericity	radius	sphericity
1#	4003.1	0.21	4003.2	0.34
2#	4006.4	0.19	4006.4	0.53
3#	3996.1	0.38	3996.3	0.53
4#	3999.9	0.61	4000.0	0.25

4 CONCLUSION

The air pin pneumatic sensor developed can be used to non-contact ultra-precision measurement. Its linear range is 20 μm , resolution reaches 0.01 μm , measuring repeatability less than ± 0.05 μm , sensitivity is over 30 mv/ μm . The gauge with multi-nozzles has been used in a computer-based system for measuring spherical radius and sphericity on hemisphere contour of astronautic gyro. The present system enables a non-contact measurement with uncertainties down to ± 0.5 μm for measuring range within 20 μm . The pneumatic measurement technique presented in this paper can also be used to measure dimensions and form errors on different three dimension contours of precision machine parts.

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