DEVELOPMENT OF PNEUMATIC BALL PROBE FOR MEASURING SMALL HOLE

Kiyoshi Takamasu *, Kuo Chih-Che, Akihiro Suzuki,
Masahiko Hiraki, Ryoshu Furutani and Shigeo Ozono
***** Department of Precision Engineering, The University of Tokyo
Hongo 7-3-1, Bunkyo-ku, Tokyo 113, JAPAN,
Phone: +81-3-3812-2111 Ext. 6450, Facsimile: +81-3-3812-8849
E-mail: takamasu@pe.u-tokyo.ac.jp

ABSTRACT

A novel touch probe using a pneumatic system has been developed. This pneumatic probing system consists of a small ball, a thin pipe, a vacuum generator and a differential pressure sensor. Basic concepts and theoretical analysis of the pneumatic ball probe are described. A first prototype of the probe is made and tested. From the theoretical analysis and the experimental tests, the probe is found to measure a diameter of a small hole by very low measuring force.
Keywords: pneumatic sensor, ball probe, two-dimensional sensor.

1 INTRODUCTION

The measurement of a diameter of a small hole with low measuring force and a high resolution is one of key issues for evaluating products in the industry of semiconductor and micro machining. However, there is no good sensing system to measure the diameter of a small hole by very low measuring forces.

Therefore, we have developed a novel sensing system using a pneumatic system for measuring the diameter of a small hole. The sensor consists of a small ball, a thin pipe, a vacuum generator and a differential pressure gauge. In this sensor, the small ball is kept at the center of the thin pipe by the vacuum pressure. When the ball touches a wall of a small hole, the ball is shifted from the center of the pipe and it causes the airflow. The differential pressure gauge detects the airflow, then the sensor finds the point of touching between the small ball and the wall of the small hole.

We made the first prototype of the pneumatic ball probe, from theoretical and experimental analysis; we describe the following items for developing the pneumatic ball probe;

- the basic concept of the probe,
- the theoretical analysis of measuring force of the probe,
- the theoretical analysis for detecting the differential pressures at the pipe of the probe,
- the experimental results of relationship between the displacement of the ball and the sensing pressure.

2 BASIC CONSTRUCTION AND TARGET SPECIFICATION

Now we are ready to consider the basic construction of the pneumatic ball probe. The pneumatic ball probe basically consists of a small ball as a stylus tip and a thin pipe as a stylus shaft (see Fig. 1). The small ball is kept at the center of the pipe by the vacuum pressure. Therefore, the small ball is shifted when the ball touches the wall of a small hole by very small measuring force. The shift of the ball causes airflow from outside to inside of the probe.

This directly demands the airflow in the probe make the change of pressure inside of the probe. From this, we can detect the airflow using the pressure sensor.

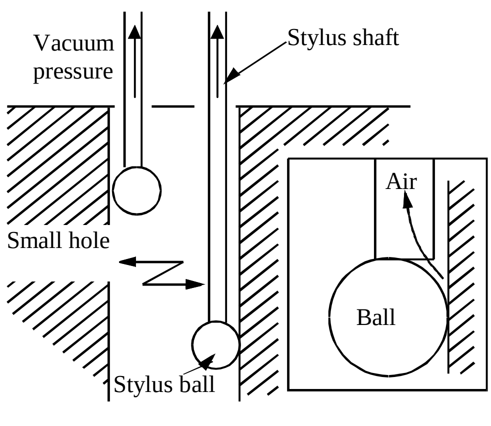

Fig. 1 Basic construction of the pneumatic ball probe.

We have the following target specifications of the pneumatic ball probe;

- the diameter of the small ball is from 0.1 mm to 1 mm,
- the measuring force is smaller than 0.001 N,
- the measuring resolution is up to 0.1 µm.

3 BASIC PRINCEPLE OF PNEUMATIC BALL PROBE

From the basic construction and the target specifications of the pneumatic ball probe, we analyze the basic properties of the probe; such as a measuring force of the probe, an opening area of the pipe, and changes of pressures and flows in the probe.

3.1 Measuring Force

The quantity of a measuring force of the pneumatic ball probe is obtained from the analysis of moments at point E (see Fig. 2). Equation (1) shows the balance of moments at point E, when the ball touches the wall. Solving the equation (1) for the measuring force F, the equation (2) is obtained.

$$F_p r - Mgr - F\sqrt{R^2 - r^2} = 0\,. \tag{1}$$

$$F = \frac{(F_p - Mg)r}{\sqrt{R^2 - r^2}}\,. \tag{2}$$

Where F_p is the force of the vacuum pressure to support the ball upward, M is the mass of the small ball, g is the gravity constant, R is a radius of the small ball and r is an internal radius of the thin pipe. In these equations, friction between the ball and the pipe, and the ball and the wall are disregarded. The vacuum force F_p and the mass of ball M are expressed as follows;

$$F_p = \pi r^2 P_V\,, \tag{3}$$

$$M = \frac{4}{3}\pi R^3 \rho_S\,, \tag{4}$$

where P_V is the vacuum pressure and ρ_S is the density of the ball. We substitute equations (3) and (4) into equation (2), we obtain the quantity of measuring force F as the following equation;

$$F = \frac{\pi r}{\sqrt{R^2 - r^2}}\left(r^2 P_V - \frac{4}{3}R^3 \rho_S g\right). \tag{5}$$

Fig. 3 indicates the relationship between the measuring force F and the ratio R/r at the internal radius of the pipe is 0.05 mm, 0.1 mm or 0.2 mm, when the vacuum pressure is 10 kPa and the density of the ball (made of steel) is 7900 kg/m^3.

From these equations and the figure, we easily set the measuring force of the probe smaller than 0.001 N, when the ratio R/r is over 1.1 and the internal radius of the pipe r is smaller than 0.1 mm. We conclude that the measuring force of the pneumatic ball probe can be set at the value of

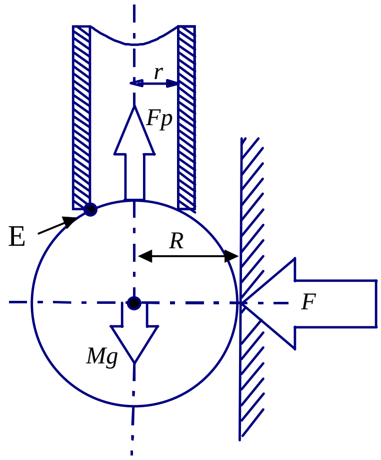

Fig. 2 Measuring force *F* of the pneumatic ball probe from the moment balance at point E.

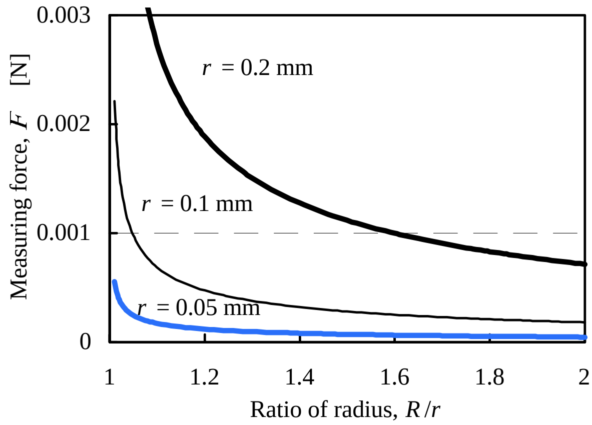

Fig. 3 Measuring force *F* Vs the radius ratio *R/r* at the internal radius *r* of the pipe is 0.05 mm, 0.1 mm or 0.2 mm.

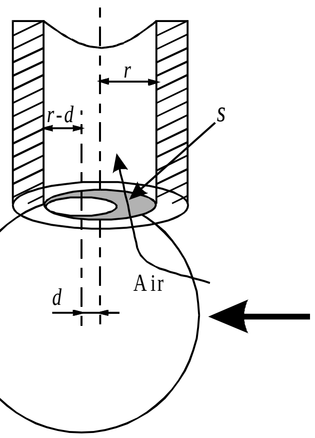

Fig. 4 Opening area *s* between the pipe and the ball where an airflow moves from outside to inside of the pipe.

the target specification when the radius of the pipe is smaller than 0.1 mm.

3.2 Pressure Changes in the Probe

Keeping this in mind, we will next consider how to detect airflow in the probe when the ball is shifted by touching the wall of a small hole.

Firstly, we calculate an opening area between the ball and the pipe. When the ball is shifted, an opening area *s* between the ball and the pipe is opened. The opening area where airflow from outside to inside of the pipe is indicated in Fig. 4. The area *s* of the opening is calculated from equation (6) to relate the displacement of the ball *d*;

$$s = \pi r^2 - \pi(r-d)^2 = \pi(2rd - d^2)\,. \qquad (6)$$

Secondly, we will consider velocities and pressures of the airflow at the top, inside and at the end of the probe. Fig. 5 shows the airflow, in this figure, a small opening (area is *s*) simulates the small ball and the thin pipe at the top of the probe and a cylinder expresses the sensing position of the probe. Then, P_O is the atmosphere pressure outside of the probe and P_A is the sensing pressure in the probe, P_v is the vacuum pressure, and the velocities of the air flows from outside to inside and inside of the probe are v_A and v_B, respectively.

From Bernoulli's theorem, momentum theorem and equation of continuity, we obtain equation (7) at the top of the probe, equation (8) at the end of the probe and equation (9) as follows;

$$v_A^2 + h v_A^2 = \frac{2(P_O - P_A)}{\rho_a}\,, \qquad (7)$$

$$\rho_a s v_A^2 - \rho_a a v_B^2 = (P_A - P_V)a\,, \qquad (8)$$

$$v_A s = v_B a\,. \qquad (9)$$

Where ρ_a is the density of air, *h* is a coefficient of energy loss in proportion to the square of the velocity at the top of the probe and *a* ($a = \pi r_a^2$) is the area of the sensing position of the probe. From equations (7), (8) and (9), we obtain the inside pressure of the probe P_A;

$$P_A = \frac{a^2(1+h)P_V - 2asP_O + 2s^2 P_O}{a^2(1+h) - 2as + 2s^2}\,. \qquad (10)$$

In this connection, we detect the difference pressure ΔP between the pressure at the sensing position P_A and the vacuum pressure P_V. The differential pressure ΔP is calculated from equation (10) as follows;

$$\Lambda P = P_V - P_A = \frac{2(a-s)s}{(1+h)a^2 - 2as + 2s^2}(P_O - P_V)\,. \qquad (11)$$

Fig. 6 shows the theoretical relationship between the differential pressure ΔP and the shift of ball *d* from equations (6) and (11) at the conditions of the internal radius of the pipe *r* = 0.2 mm or *r* = 0.5 mm (the other conditions: *R* = 1 mm, r_a = 3 mm, *a* = 28.3 mm^2, P_O–P_V = 9.2 kPa, *h* = 0.5, see fig. 9). This figure implicitly demands

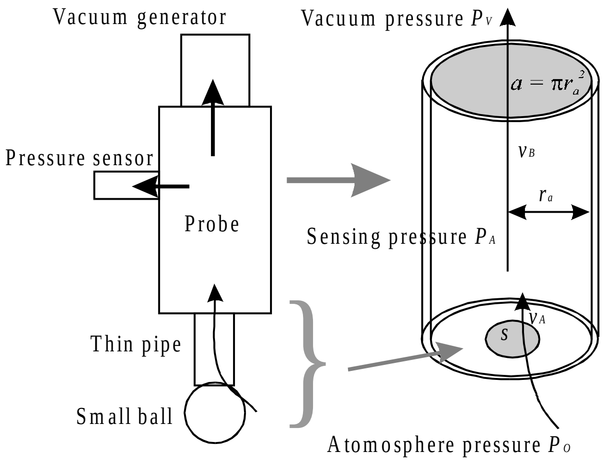

Fig. 5 Model of the airflow in the probe.

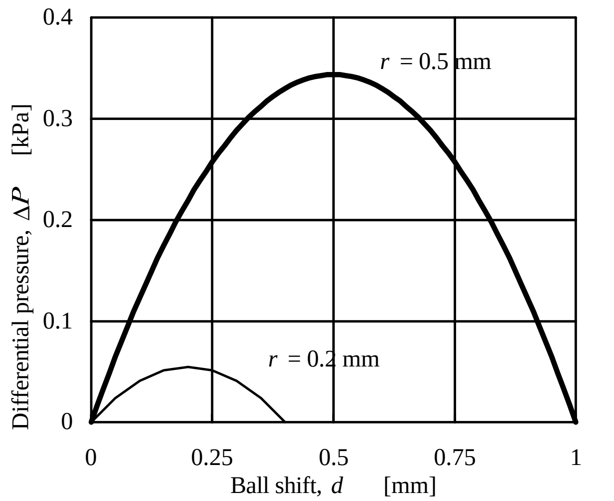

Fig. 6 Theoretical calculation of the differential pressure ΔP Vs the ball shift *d* at the internal radius of the probe *r* = 0.5 mm or *r* = 0.2 mm.

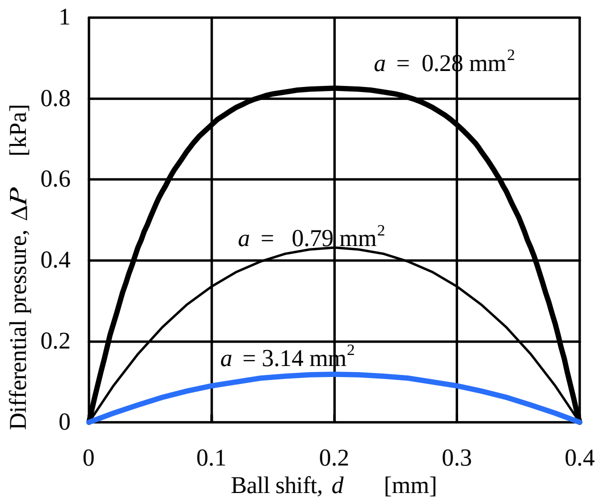

Fig. 7 Theoretical calculation of the differential pressure ΔP Vs the ball shift *d* at sensing area *a* = 0.28 mm^2, *a* = 0.79 mm^2 or *a* = 3.14 mm^2.

that the smaller internal radius r cause the smaller pressure changes and the smaller measuring range of the ball shift.

Fig. 7 displays the change of the differential pressure when the sensing area $a = 0.28\ mm^2$, $a = 0.79\ mm^2$ or $a = 3.14\ mm^2$ (for r_a = 0.3 mm, 0.5 mm and 1 mm respectively), r = 0.2 mm, h = 5.0 and the other conditions are same as these in fig. 6. This figure results in that the small pressure changes are obtained when the sensing area is wide.

4 EXPERIMENTS

Fig. 8 illustrates an experimental setup of the pneumatic ball probe. A compressor and a vacuum generator provide the vacuum pressure to the probe, and a differential pressure sensor (Toyoda, AA6000H200D, measuring range is 0 to 200 mmH_2O) detects the differential pressure from the probe, then outputs digital signals to a personal computer system. A stage (resolution is 1 μm) and a stage controller which controlled by the computer system shift the ball of the probe.

The first prototype of the probe is illustrated on figs. 9 and 10. The internal radius r of the pipe is 0.2 mm or 0.5 mm, the radius of the ball R is 0.5 mm or 1 mm and the radius of the probe at the sensing position r_a is 0.3 mm, 0.5 mm, 1 mm or 3 mm. Then, we supply the vacuum pressures (−9.2kPa from the atmospheric pressure) and shift the stage step by step.

Fig. 11 shows one of example of the relationship between the differential pressure ΔP and the stage displacement d in the conditions as the same in fig. 6. It is find that the theoretical graph (fig. 6) has almost same figure and tendency of the experimental graph (fig. 11).

Fig. 12 displays the relationship between the differential pressure ΔP and the stage displacement d in the same conditions as fig. 7. From figs. 7 and 12, we can conclude that qualitative relationship of the theoretical analysis (equations (6) and (11)) have the good agreements with the experimental results. However, we select the value of h from the experimental results, in consequence of this, we need further theoretical analysis especially on the energy loss of the airflow.

5 CONCLUSION

We can reach the following conclusions from the theoretical analysis of the pneumatic ball probe and the experimental results of the first prototype of the probe.

- The basic concept of the pneumatic ball probe is explained to measure the diameter of the small hall with very low measuring force.
- The measuring force of the pneumatic ball probe can be set at less than 0.001 N when the radius of the pipe is smaller than 0.1 mm.
- The theoretical equation for the relationship between the differential pressure and the shift of

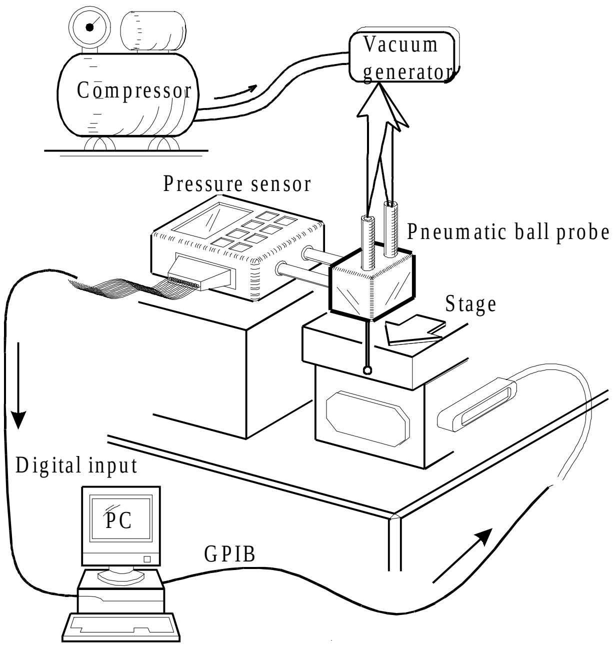

Fig. 8 Experimental setup for the pneumatic ball probe.

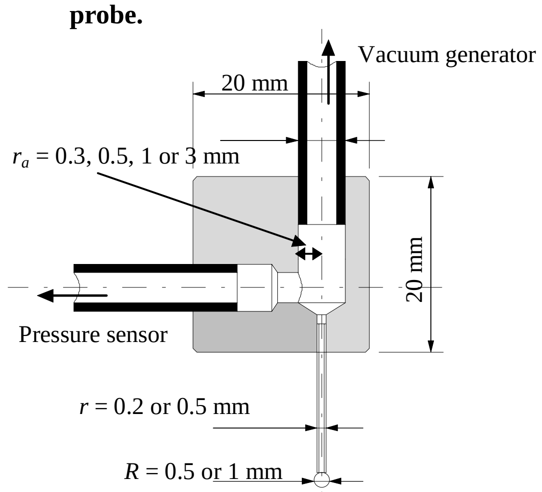

Fig. 9 Cross sectional drawing of the first prototype of the pneumatic ball probe

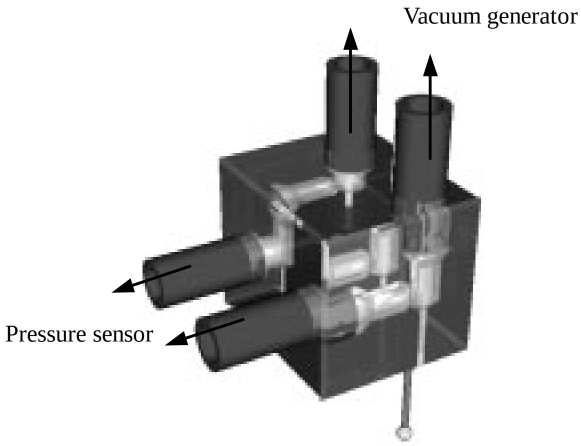

Fig. 10 Three-dimensional view of the first prototype of the probe.

ball is obtained.

- The first prototype of the pneumatic ball probe is made and tested.
- The experimental results have the good agreements to the theoretical analysis qualitatively.
- The coefficient of energy loss in proportion to the square of the velocity of airflow is not derived from the theoretical analysis.

We have to do the following items for the future works.

- The smaller prototype will be made to measure the small hole.
- The energy loss of the airflow will be analyzed precisely.
- The error estimation will be made for the pneumatic ball probe in measurement.

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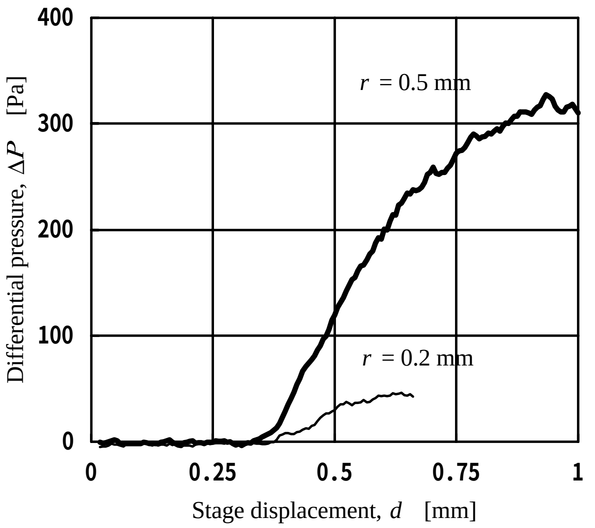

Fig. 11 Example of the experimental outputs of the differential pressure Δ*P* Vs the stage displacement *d* at the internal radius of the probe *r* = 0.5 mm or *r* = 0.2 mm.

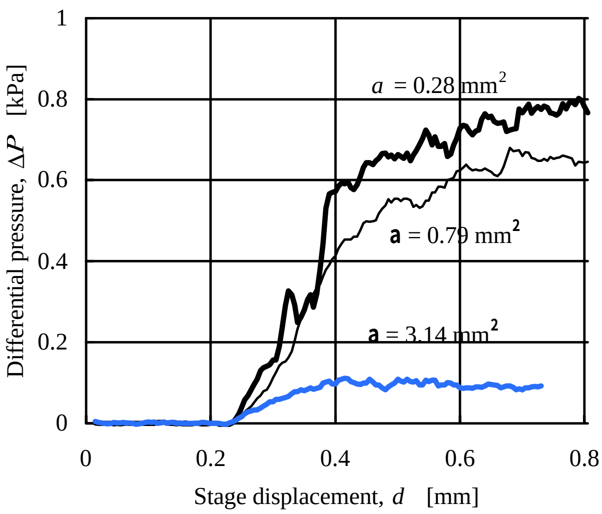

Fig. 12 Experimental outputs of the differential pressure Δ*P* Vs the stage displacement *d* at sensing area *a* = 0.28 mm^2, *a* = 0.79 mm^2 or *a* = 3.14 mm^2.