Int. J. Japan Soc. Prec. Eng., Vol. 33, No. 3 (Sept. 1999) Paper

Development of a Pneumatic Ball Probe (1st Report)*
– Basic Construction –

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The ability to measure the diameter of a small hole with low measuring force and high resolution is one of the key issues in product evaluation in the semiconductor and micro machining industry. Currently there is no popular sensing system for this type of measurement, so we have developed a novel pneumatic sensing system to solve this problem. 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, which causes air to flow from the outside to the inside of the pipe. The differential pressure gauge detects the airflow, and the sensor registers the contact between the small ball and the wall of the small hole. A first prototype of the pneumatic ball probe has been made and tested. Based on the theoretical analysis and the results of experimental tests, it appears that the probe can detect the contact of the ball.

Key words: pneumatic sensor, ball probe, two-dimensional sensor

1. Introduction

The importance of the measurement of small geometrical quantities continues to grow in the semiconductor and micro machining industry. This is a need for a probing system that can measure the size of a small machine part such as a small hole (that is, a hole with a diameter smaller than 3.2 mm in drilling) with low measuring force [1].

Small holes are used in machine parts, print boards and as many kind of nozzles. In order to machine a small hole precisely, it is important to measure the hole's inner diameter. A lot of research is underway to develop ways to make these measurements, including development of a limiting gauge method, a taper stylus method and a mechanical stylus method [2]. Masuzawa has proposed a vibrating stylus method [3].

The problems with these methods are the amount of contact made by the probe, since a small measuring force is essential. Optical and pneumatic methods [4) 5)] have a small measuring force, but the optical method is influenced by the texture of the material's surface and the size of optical instruments is often a limitation.

Pneumatic micrometers, on the other hand, are widely used to measure the size of machine parts with low measuring force [6)-8)]. We proposed a novel pneumatic measuring system known as the "Pneumatic ball probe" which consists of a small ball and a thin pipe. The basic concepts and specifications of the pneumatic ball probe are discussed herein; the prototype of the probe has been made and tested [9].

2. Basic Construction and Target Specifications

The pneumatic ball probe 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 vacuum pressure. The small ball is shifted when it

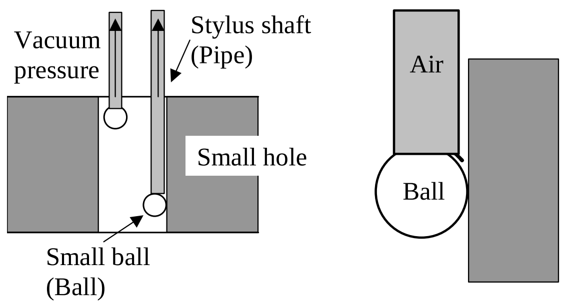

Fig. 1 Basic construction of the pneumatic ball probe

* Received in February 20, 1998 in Japanese and March XX, 1999 in English
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touches the wall of a small hole with a very small measuring force. The shift of the ball causes airflow from outside to the inside of the probe, which change the pressure inside the probe. This pressure change is then measured with a pressure sensor.

Our target specifications for the pneumatic ball probe were as follows:

(1) The diameter of the small ball is from 0.1 mm to 1.0 mm.
(2) The measuring force is smaller than 0.001 N.
(3) The measuring resolution is up to 1 µm.
(4) Deviations from sphericity of the small ball or roughness at the top of the pipe is better than 1 µm.

3. Basic Analysis of the Pneumatic Ball Probe

3.1 Analysis of Measuring Force

The quantity of the pneumatic ball probe's measuring force 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 equation (1) for the measuring force F, equation (2) is obtained, as follows:

$$F_P \frac{d}{2} - Mg\frac{d}{2} - F\sqrt{\frac{D^2-d^2}{4}} = 0\,, \tag{1}$$

$$F = \frac{(F_P - Mg)d}{\sqrt{D^2-d^2}}\,, \tag{2}$$

where F_p is the force of the vacuum pressure need to support the ball upward, M is the mass of the small ball, g is the gravity constant, D is the diameter of the small ball and d is an internal diameter of the thin pipe. In these equations, friction between the ball and the pipe and between the ball and the wall are disregarded. The vacuum force F_p and the mass of ball M are expressed as follows:

$$F_P = \frac{1}{4}\pi d^2 P_V\,, \tag{3}$$

$$M = \frac{1}{6}\pi D^3 \rho_S\,, \tag{4}$$

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

$$F = \frac{\pi d}{\sqrt{D^2-d^2}}\left(\frac{1}{4}d^2 P_V - \frac{1}{6}D^3 \rho_S g\right). \tag{5}$$

Fig. 3 indicates the relationship between the measuring force F and the ratio D/d, 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 can

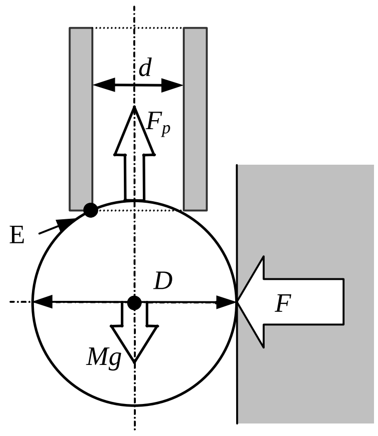


Fig. 2 Measuring force F of the pneumatic ball probe from the moment balance at point E

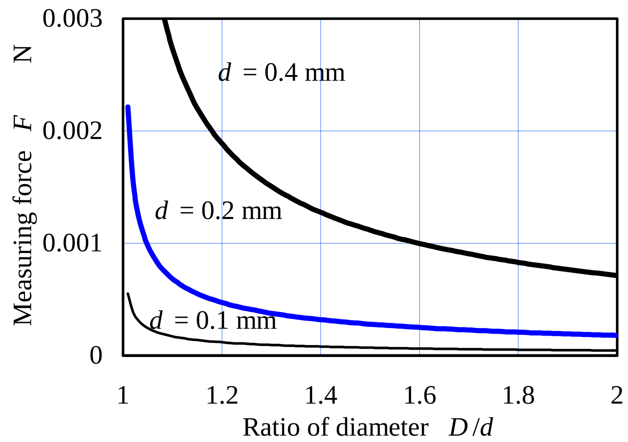


Fig. 3 Measuring force F versus diameter ratio D/d for the internal diameter d is 0.1 mm, 0.2 mm and 0.4 mm

determine that the measuring force of the probe is smaller than 0.001 N, when the ratio D/d is over 1.1 and the internal diameter of the pipe d is smaller than 0.2 mm. Our target specifications are also satisfied when the ratio D/d is 2.0 and the internal diameter is 0.4 mm. Moreover, under these conditions, a bending of the pipe by the measuring force is smaller than 1 µm.

From equation (5) we see that if the force of vacuum pressure degrees is at the upper limit needed to support the mass of the ball, the measuring force becomes smaller. However, the smaller vacuum force causes the support to be unstable. We plan to do further tests to determine the optimum condition of the vacuum pressure for this application.

3.2 Pressure Changes in the Probe

To measure pressure changes in the probe, we first determined the location and size of an opening in the pipe that would allow air to flow into the pipe. The opening area s where airflow occurs from outside to the inside of the pipe is indicated in Fig. 4. The area s is calculated from equation (6) to relate the displacement of the ball e as follows:

$$s = \frac{1}{4}\pi d^2 - \pi\left(\frac{d}{2} - e\right)^2 = \pi(de - e^2)\,. \qquad (6)$$

Second, we consider velocities and pressures of the airflow at the top, inside and at end of the probe. Fig. 5 shows the model of pressure changes and airflow in the probe, where, P_O is the atmospheric pressure outside of the probe and P_A is the sensing pressure in the probe, P_v is the vacuum pressure, and the airflow velocities from outside to inside and inside probe as well as within the probe are v_A and v_B, respectively.

From Bernoulli's theorem, momentum theorem and the 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 [10) 11)]:

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

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

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

where ρ_a is the density of air, h is a coefficient of energy loss in proportion to the squares of the velocity at the top of the probe and a 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 .

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

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

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

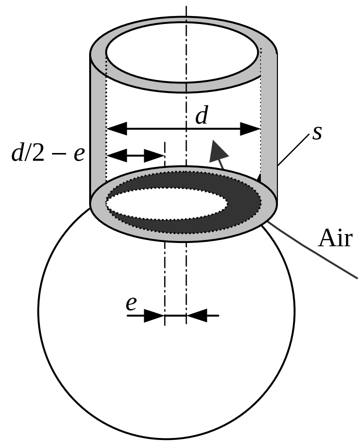


Fig. 4 Opening area s between the pipe and the ball

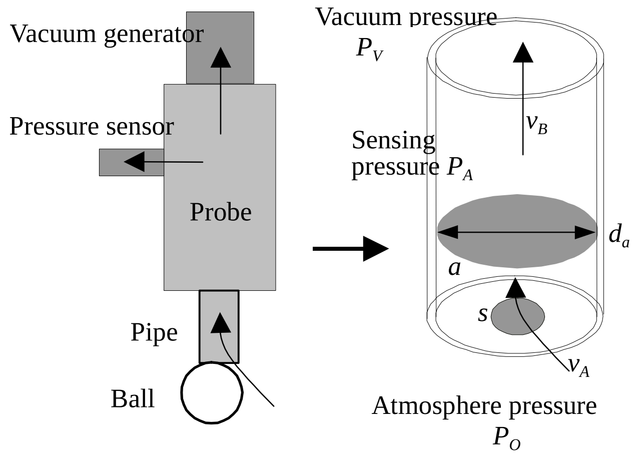


Fig. 5 Model of the airflow in the probe

Fig. 6 shows the theoretical relationship between the differential pressure ΔP and the shift of ball e from equations (6) and (11). To continue the analysis, we assigned internal diameters of the pipe to be d = 0.4 mm or d = 1.0 mm (the other conditions: d_a = 3 mm, P_O–P_V = 9.2 kPa, h = 5.0). We decided to match the experimental data with the theoretical data when assessing the value of energy loss. This figure

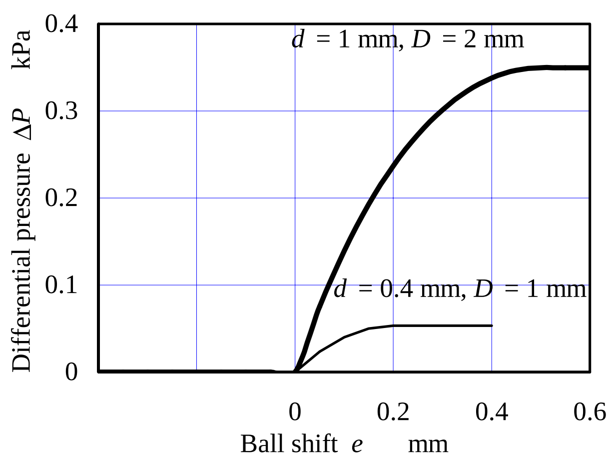


Fig.6 Theoretical calculation of the differential pressure ΔP versus the ball shift e for the internal diameter of the probe

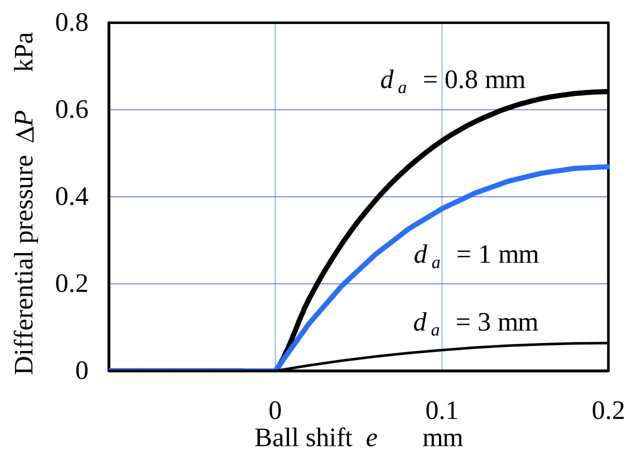


Fig. 7 Theoretical calculation of the differential pressure ΔP versus the ball shift e for the diameter of the sensing area

implicitly demands that the smaller internal diameter *d* causes smaller pressure changes and a smaller measuring range of the ball shift. The maximum pressure is observed when the ball shift *e* is *d*/2.

Fig. 7 displays the change in differential pressure when the diameter of the sensing area d_a = 0.8 mm, 1 mm and 3 mm and the other conditions are the same as those in Fig. 6. The results are that small pressure changes are obtained when the sensing area is wide.

4. Basic Experiments of Pneumatic Ball Probe

4.1 Construction of Basic Experiments

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

The first prototype of the probe is illustrated on Fig. 9. The internal diameter *d* of the pipe is 0.4 mm or 1 mm, the diameter of the ball *D* is 1 mm or 2 mm, the diameter of the probe at the sensing position d_a is 0.8 mm, 1 mm or 3 mm, the diameter of the pipe is 0.8 mm or 1.5 mm, and the length of the pipe is 15 mm or 20mm. We supplied vacuum pressures (–9.2kPa from the atmospheric pressure) and shifted the stage step by step.

4.2 Relationship between Ball Shift and Differential Pressure

Fig. 10 indicates that the ball (diameter 2 mm) is kept at the top of pipe (inner diameter 0.4 mm) by the vacuum pressure. When the ball shift is large, the ball is still stable, as shown in Fig. 10 (b).

Fig. 11 shows one example of the relationship between the differential pressure Δ*P* and the stage displacement *f* in the same conditions as those in Fig. 6. We found that the theoretical graph (Fig. 6) had almost the same figures and tendencies as the experimental graph (Fig. 11). In these graphs, the horizontal scales are not in agreement, because stage displacement is used instead of a ball shift in Fig. 11. Furthermore, the coefficient of energy loss *h* is assumed as 5.0 so that the experimental data and the theoretical data agree.

The origin of the vertical scale of the graph in Fig. 11 is the average pressure when the ball shift is zero. If the area of ball shift is large (that is, if *f* is larger than 0.6 mm), the differential pressure varies unstably. On the other hand, if the area of ball shift is small (if *f* is 0.3 mm to 0.4 mm), the fluctuation of the differential pressure of the inner diameter of 0.4 mm is larger than

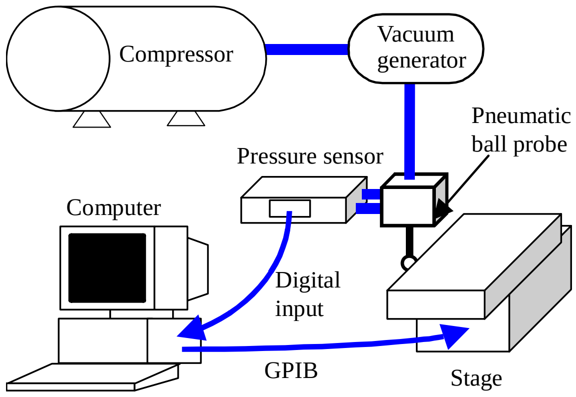


Fig. 8 Experimental setup of the pneumatic ball probe

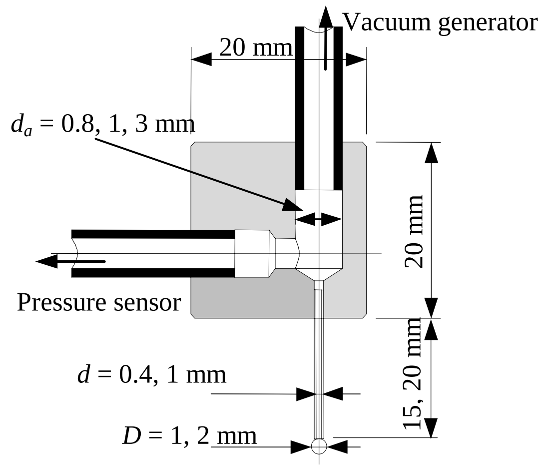
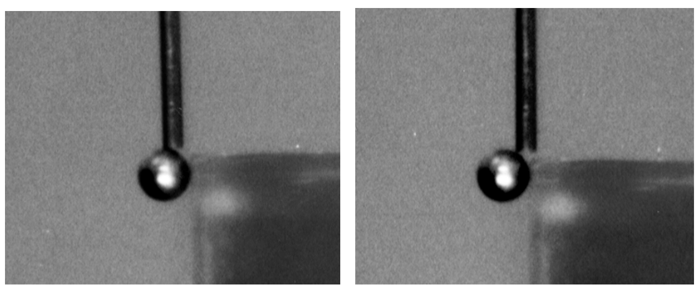


Fig. 9 Cross sectional drawing of the first prototype of the pneumatic ball probe



(a) $e \cong 0.3$ mm (b) $e \cong 0.8$ mm

Fig. 10 Photograph of the ball at the top of pipe for diameter of ball *D* is 2 mm and internal diameter of pipe *d* is 0.4 mm at ball shift *e* is 0.3 mm and 0.8 mm

that of the inner diameter of 1 mm. This is because the vacuum generator and the differential pressure sensor are not stable if the pressure load is high.

4.3 Relationship between Differential Pressure and Ball Shift

In order to miniaturize the probe, the diameter of the ball has to be small. When the diameter of the ball becomes small, the inner diameter of the pipe also can be small and the change of differential pressure can be small. The result is that the diameter of the sensing area becomes small in order to magnify the change of the differential pressure.

Fig. 12 displays the relationship between the differential pressure ΔP and the stage displacement f under the same conditions as Fig. 7. From Figs. 7 and 12 we can conclude that the qualitative relationship between the theoretical analysis and the experimental results is good. In Fig. 12, the differential pressure is averaged over the span of 1 sec (sampling interval is 0.2 sec) to reduce the influence of the instability of the vacuum generator and the pressure sensor.

When the diameter of the sensing area is small, the amount of airflow becomes small and the energy loss increases. In this condition, the pressure load is high, the vacuum generator becomes unstable and there is a limited pressure gain.

4.4 Evaluation of Resolution of the Probe

The contact signal is detected when the differential pressure is greater than the threshold pressure, which is the average pressure when the ball shift is zero. Fig. 13 shows the pressure fluctuation in 30 sec when the ball shift is zero. The thin line indicates the pressure during a 0.1-sec sampling interval, and the thick line indicates the average pressure in 1 sec. The standard deviation (±2σ) of the pressure fluctuation of raw pressure and the averaged pressure are ±4.9 Pa and ±1.4 Pa, respectively.

Fig. 13 (b) shows the slope of the beginning point of the pressure change in Fig. 12. The resolution of the probe can be calculated from the pressure fluctuation and the slope of the pressure change as Fig. 13 (b). Table 1 lists the resolution of the probe, which relates to the averaging and the internal diameter of the sensing area.

At the present time, the resolution obtained does not reach the level of the target resolution. We will continue to try to increase the resolution of the probe.

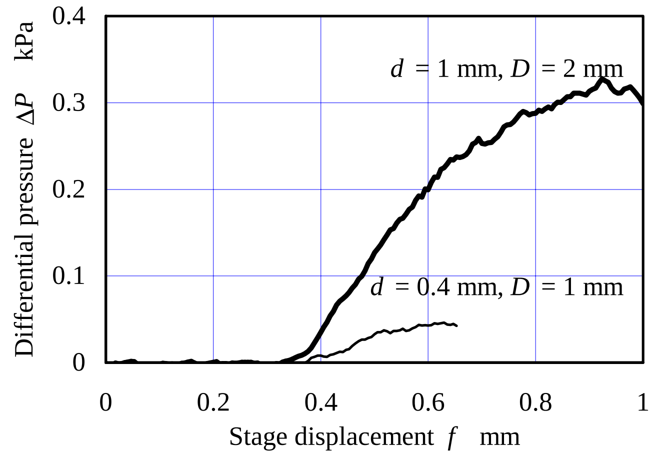


Fig. 11 Differential pressure ΔP versus the stage displacement f for the internal diameters of the pipe d is 0.4 mm and 1 mm

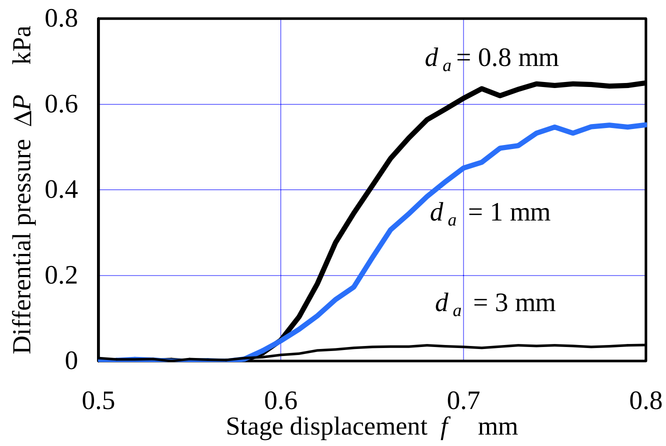
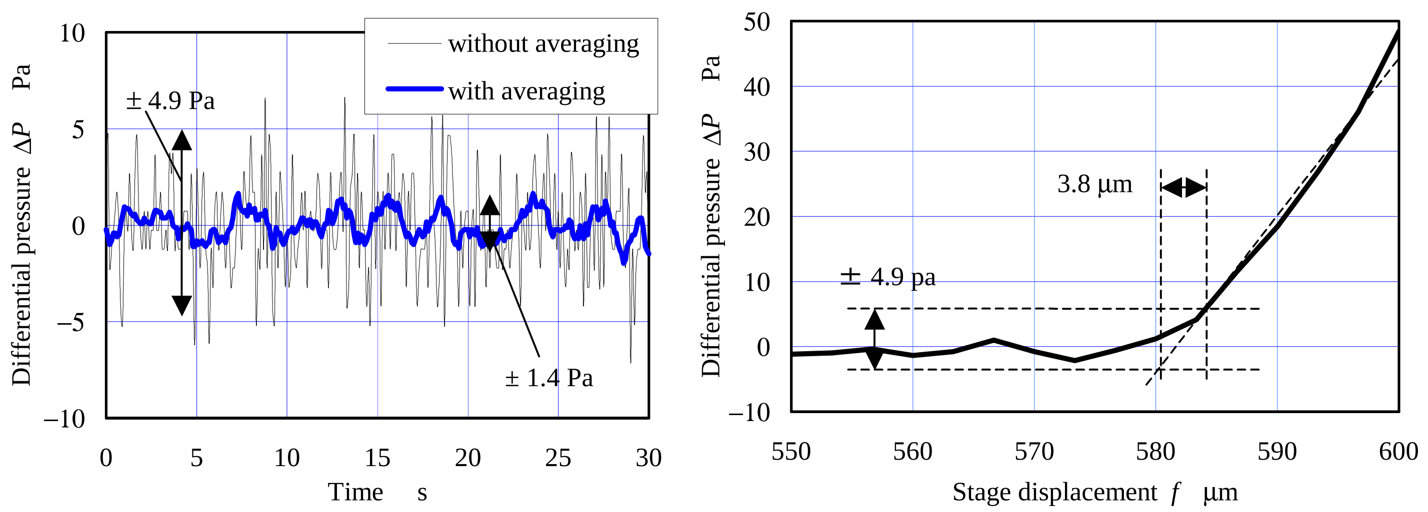


Fig. 12 Differential pressure ΔP versus the stage displacement f for the diameter of the sensing area d_a is 0.8 mm, 1 mm and 3 mm



(a) Fluctuation of the differential pressure in 30 sec with/without averaging

(b) Differential pressure at the ball shift is small for the internal diameter of the sensing area is 0.8 mm

Fig. 13 Resolution of the pneumatic ball probe by the fluctuation of the pressure and the slope of the displacement-pressure curve

5. Conclusions

In this article, we described a novel pneumatic ball probe that can measure small machine parts with a small measuring force. The basic analysis and the basic experiments show that the theoretical analysis agrees with the experimental results. We reached the following conclusions:

(1) the basic construction of the pneumatic ball probe was possible,
(2) 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 0.2 mm,
(3) the theoretical equations for the relationship between the differential pressure and the shift of ball were obtained, and
(4) the first prototype of the pneumatic ball probe has been made and tested.

It is difficult to detect a small pressure change, because the energy loss increases when the size of the probe is small. Therefore, the resolution of the prototype probe does not achieve the target resolution.

We will use this type probe as a touch-sensitive probe. In this condition, we can only detect contact rather than pressure change. Developing a pneumatic ball probe sensing method that detects contact is a goal for the future.

Table 1 Resolution of the pneumatic ball probe relation to the averaging and the internal diameter of the sensing area

Internal diameter of sensing area d_a	0.8 mm	1 mm	3 mm
Without averaging	3.8 μm	5.6 μm	12.6 μm
With averaging	1.1 μm	1.6 μm	3.6 μm

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