IMEKO-XV World Congress, 1999, pp. 193-200

Development of Touch Trigger Type Pneumatic Ball Probe

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Abstract

In this paper, a novel touch trigger probe which has a totally different construction concept; namely, a pneumatic ball probe has been developed. This touch trigger type pneumatic ball probe consists of a small probe ball, a thin pipe, a pneumatic trigger sensor and a vacuum pump. The fundamental concepts and theoretical analysis of the pneumatic ball probe are described. A prototype of the probe is made and tested.

From the experimental tests, the measuring force is reduced to a great extent by using this structure of separating probe ball from stylus. The fundamental analysis and experiment showed that it is possible to measure the distance between two walls such as a groove or drilled hole without restriction of material for two dimension measurement. Using this pneumatic ball probe, it is found that the width between gauge blocks could be measured within the standard deviation of 1.1μm as well as it is influenced by the vacuum of probe and the inclination of the measurement.

Keywords: pneumatic sensor, touch trigger probe, two dimensional measurement, measuring force, hole diameter

1. Introduction

Coordinate Measuring Machines (CMMs) are now widely used in industry for a large range of measurement tasks. The increasing pressure on manufacturers to produce in small batches with tight tolerance and zero defect, forces them to intensify and optimize their quality control process. It demands for a simple probe with high accuracy for miniaturization and low damage measurement with low measuring force for measuring soft materials.

Touch trigger probes are by far the most commonly used due to their simplicity in many types of probe commercially available. But, it is well known that most conventional touch trigger probes have a large, heavy, expensive design, measuring with large trigger force, and suffering from lobing effects[1] (i.e. pre-travel variation in different probing directions).

Therefore, we have developed a novel touch trigger probe using pneumatic system. This touch trigger type pneumatic ball probe has a simple structure for miniaturization and low measuring force and no lobing effects for highly accurate measurement.

We made a prototype of the pneumatic ball probe, from theoretical and experimental analysis; we describe the following items for developing the touch trigger type pneumatic ball probe:

- The fundamental concept and aim specification
- The theoretical analysis of sensing theory
- The theoretical analysis of measuring force
- The construction of the prototype of the touch trigger type pneumatic ball probe
- The results of evaluative experiments

The fundamental concepts and theoretical analysis of the pneumatic ball probe are described. A prototype of the probe is made and tested.

2. Fundamental Concept and Aim Specifications

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 tip by 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 the airflow flowing from outside to inside of the probe.

This directly demands the airflow in the probe make some pneumatic changes inside of the probe. From this, we can probe the touch by detecting the airflow using some pneumatic sensors.

We have the following aim specifications of the pneumatic ball probe:

- The diameter of small ball using as stylus tip is from 0.1 mm to 1 mm,
- The length of the pipe using as stylus shaft is longer than 10 mm,
- The measuring force is smaller than 0.001 N,
- The measuring resolution is up to 0.1 μm.

3. Theoretical Analysis[2]

From the fundamental concept and the aim specifications of the pneumatic ball probe, we analyze the basic properties of the probe; such as a sensing theory, and a measuring force theory.

3.1 Sensing Theory

Due to the touch of wall of hole, it makes probe ball shift away from the tip of pipe. Then air is flowing through the opening area, where is on the tip of pipe between probe ball and pipe.

Firstly, we should calculate the opening area A_1 between the probe ball and pipe tip. Fig. 2 shows the model of opening situation when probe ball shifted a displacement e from the central line of pipe. The opening area A_1 is calculated from equation (1) to relate the displacement of the probe ball e :

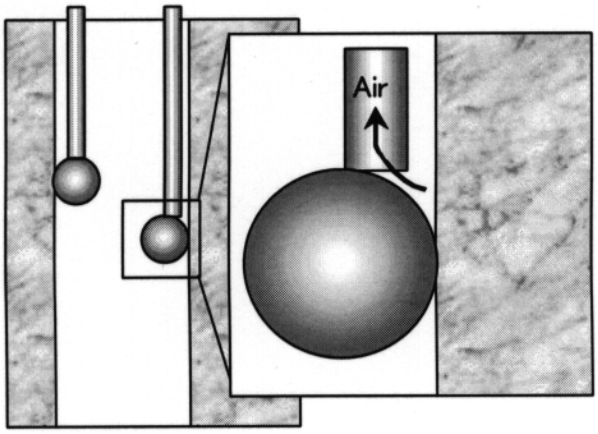

Fig. 1 Fundamental concept of pneumatic ball probe

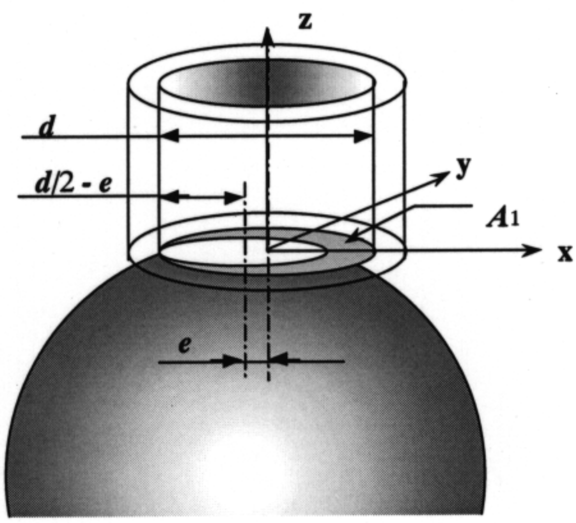

Fig. 2 Opening area A_1 on tip of pipe where the air flows into

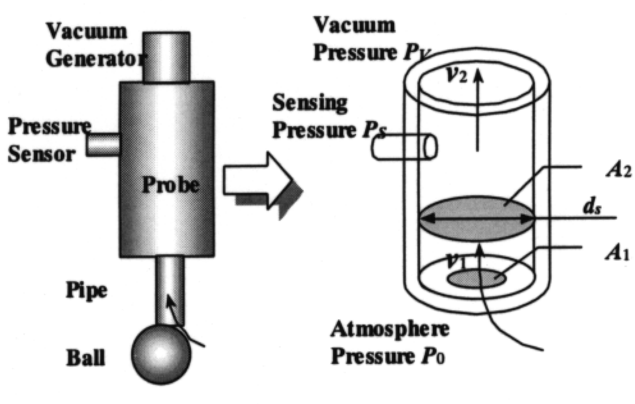

Fig. 3 Model of the airflow in the pipe

$$A_1 = \frac{1}{4}\pi d^2 - \pi(\frac{d}{2} - e)^2 = \pi(ed - e^2) \quad (1)$$

Secondly, we will consider velocities and pressures of airflow inside the probe due to the change of opening area. **Fig. 3** shows the inside shape of probe on left, and we model it in a cylinder shape with a small area A_1 as inlet and an area A_2 as outlet on right. The small area A_1 simulates the changing area on the tip of pipe.

According to Bernoulli's theorem, momentum theorem and flux of continuity, we obtain equation (2) at the top of probe, equation (3) at both tips of probe and equation (4) as follows :

$$(1+h){v_1}^2 = \frac{2(P_0 - P_S)}{\rho_{air}} \quad (2)$$

$$\rho_{air} A_1 {v_1}^2 - \rho_{air} A_2 {v_2}^2 = (P_S - P_V)A_2 \quad (3)$$

$$v_1 A_1 = v_2 A_2 \quad (4)$$

Where h is a coefficient of energy loss in proportion to the square of the velocity at the top of probe, P_0 is the atmosphere pressure outside of probe, P_S is the sensing pressure in probe, ρ_{air} is the density of air. And A_2 is the area of the sensing position of probe, v_1 is the velocity of air flowing through A_1, v_2 is the average velocity inside probe.

From equations (2) (3) and (4), we obtain the inside pressure of probe P_S :

$$P_S = \frac{(1+h){A_2}^2 P_V + 2A_1 A_2 P_0 - 2{A_1}^2 P_0}{(1+h){A_2}^2 + 2A_1 A_2 - 2{A_1}^2} \quad (5)$$

In this connection, we detect the difference pressure ΔP between the pressure at the sensing position P_S and the vacuum pressure P_V. The differential pressure ΔP is calculated from equation (5) as follows :

$$\Delta P = P_S - P_V = \frac{2A_1(A_2 - A_1)}{(1+h){A_2}^2 + 2A_1 A_2 - 2{A_1}^2}(P_0 - P_V) \quad (6)$$

Fig. 4 shows the theoretical relationship between the differential pressure ΔP and the shift of probe ball e from equations (1) and (6) at the specifications of the internal diameter of pipe d = 0.4 mm or 1.0 mm (The other specifications : D = 1 mm or 2 mm, A_2 = 28.3 mm^2, P_0-P_V = 10 kPa, h = 0.5, also see **Fig. 3**). This figure implicitly demands that the smaller internal diameter d cause the smaller pressure changes and the smaller measuring range of the probe ball shift.

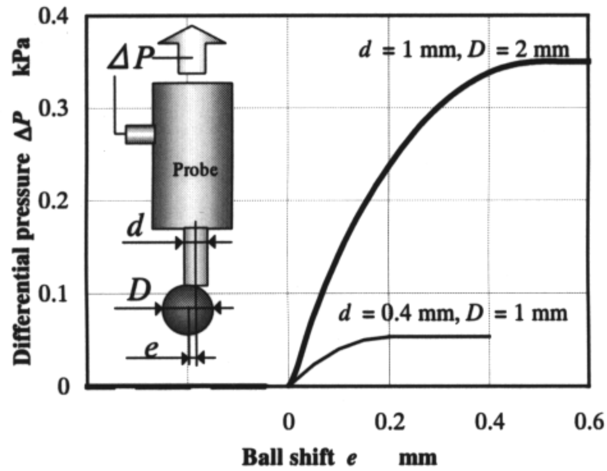

Fig. 4 Theoretical calculation of the differential pressure ΔP vs. the ball shift e

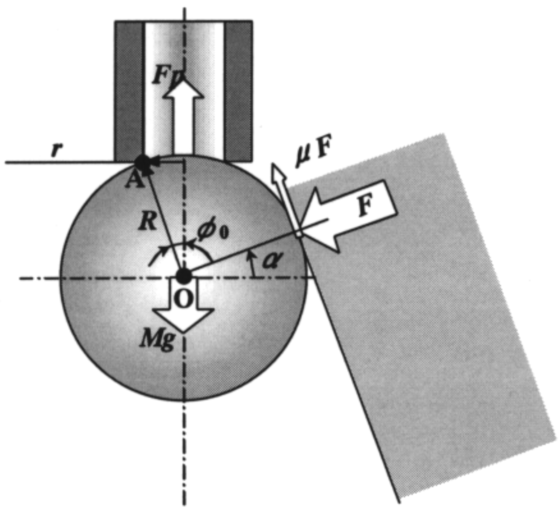

Fig. 5 Measuring Force F of the pneumatic ball probe from the moment balance at point A

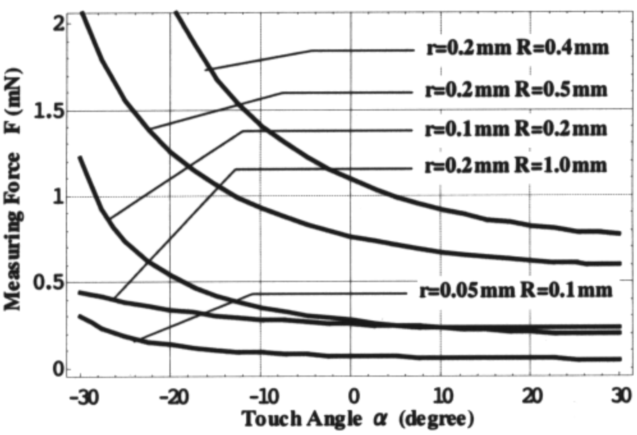

Fig. 6 Theoretical calculation of measuring force F vs. touch angle α

3.2 Measuring Force Theory

The quantity of a measuring force of the pneumatic ball probe is obtained from the analysis of moments at point A (see Fig. 5). Equation (7) shows the balance of moments at point A, when the ball touches the wall. Solving the equation (7) for the measuring force F, the equation (8) is obtained.

$$F_p r - Mgr - FR\cos(\phi_0 - \alpha) + \mu FR\{1 + \sin(\phi_0 - \alpha)\} \le 0 \quad (7)$$

$$F \ge \frac{r(F_p - Mg)}{R\{\cos(\phi_0 - \alpha) - \mu(1 + \sin(\phi_0 - \alpha))\}} \quad (8)$$

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 thin pipe. And α is the angle of measuring force direction from horizontal plane, ϕ_0 is the angle between vertical axis and OA line, μ is the friction constant.

The vacuum force F_P and the mass of ball M are expressed as follows:

$$F_p = \pi r^2 P \quad (9)$$

$$M = \frac{4}{3}\pi R^3 \rho \quad (10)$$

Where P is the vacuum pressure and ρ is the density of the ball.

We substitute equations (9) and (10) into (8), and obtain the quantity of measuring force F. Fig. 6 indicates the relationship between the measuring force F and the touch angle α at the internal radius of the pipe is 0.05 mm, 0.1 mm, or 0.2 mm, when the vacuum pressure P is 10 kPa, the density of the ball ρ is 7900 kg/m^3, and the friction constant μ is 0.2.

4. Prototype Probe

Fig. 7 shows the construction of the prototype of pneumatic ball probe. This prototype probe is mainly made up of four parts, also see Fig. 8.

The flux valve on the top of the probe, connects to vacuum pump, adjusted the flux of airflow. The body of probe, being separated to several portions in order the assembly of other parts, is made of acrylic acid resin.

The pneumatic trigger sensor in the middle of probe, consists of a light-trap sensor and an indicative ball,

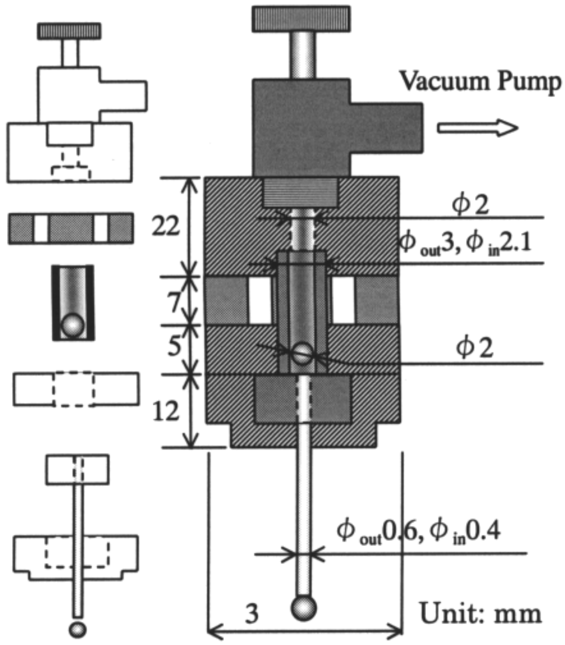

Fig. 7 Block diagram of prototype

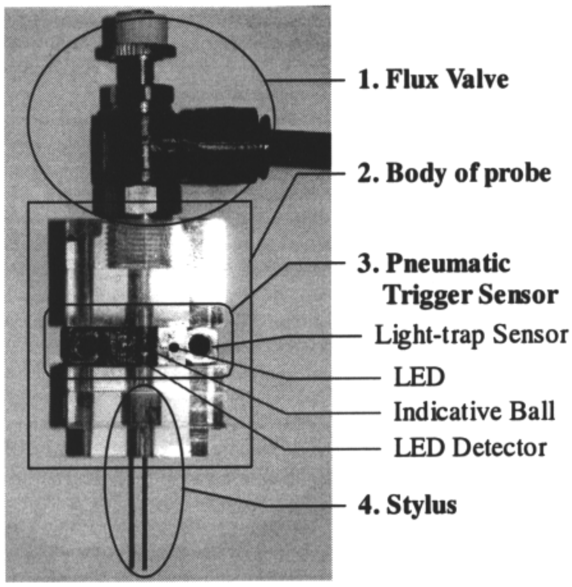

Fig. 8 Prototype of pneumatic ball probe

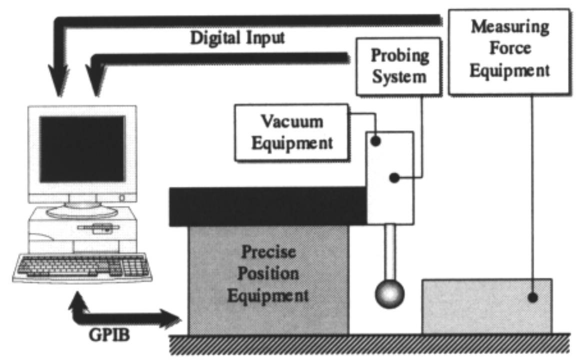

Fig. 9 Evaluation experiment system

detects the airflow inside the probe. When there is no (or just weak) flux flowing in the probe, the indicative ball would be inside of light-trap sensor shutting off light between LED and LED-Detector. On the contrary, when the flux is strong enough to push the indicative ball up out of light-trap sensor, the light will run through the gape between LED and LED-Detector.

The stylus consists of a small ball and a thin pipe. The diameter of small ball, being made of steel, is 1 mm or 2 mm. The inner and outer diameters of thin pipe, being made of brass, are 0.4 mm and 0.6 mm.

5. Evaluative Experiments

In the experiments of "Fundamental Evaluation" and "Evaluation of Sensing Methods", we control a moving stage moving approach to the probe and record the experimental data with computer, in order to reduce the exogenous effects, like vibration etc.

However in the experiments of "Evaluation of Measuring Force" and "Evaluation of Accuracy", we control the moving stage to move the prototype probe approaching to a measuring force equipment or a fix stage (groove gauge) and record the experimental data with computer (see Fig. 9). Because we want to evaluate it in the environment as close as possible to the real measuring machine.

5.1 Fundamental Evaluation[2]

Before making the prototype of pneumatic ball probe (showed in section 4.), we make some fundamental experiments with changing the diameters of stylus pipe and inner pipe.

Fig. 10 illustrates the examples of experimental results of the differential pressure vs. stage displacement at two specification sets of stylus pipe and probe ball. Because we can not certainly know the position of touch point, we express stage displacement f instead of probe ball shift e as horizontal axis. Also, from Fig. 10 and Fig. 4, we can demonstrate that the qualitative relationship of the theoretical analysis (equations (1) and (6)) have the good agreements with the experimental results.

According to the results of these fundamental evaluation experiments, we choose the optimized size of pipeline specifications (the inner diameters of pressure sensing position and stylus are ϕ 0.8 mm and ϕ 0.4 mm) that can

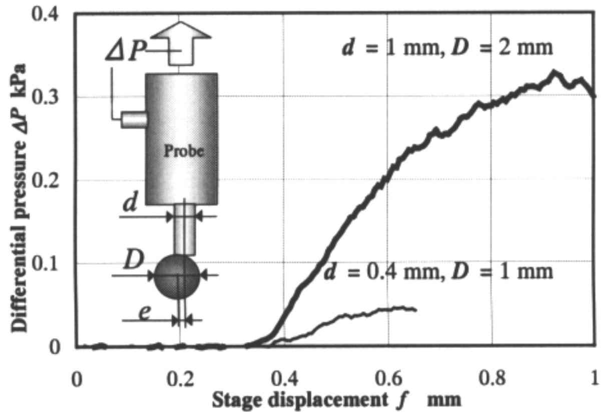

Fig. 10 Example of the experimental results at the diameters of stylus pipe d=0.4 mm and 1 mm

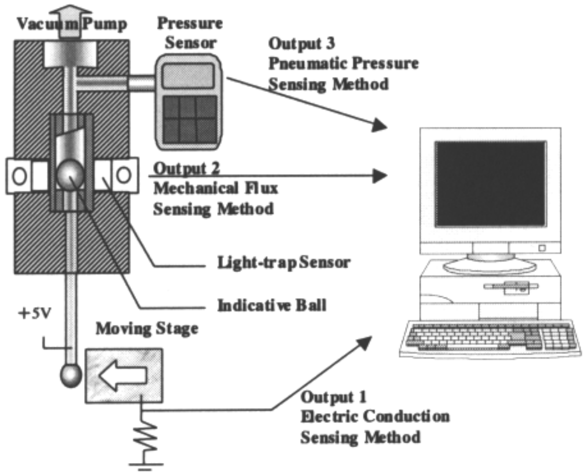

Fig. 11 Experimental system of evaluation of sensing methods

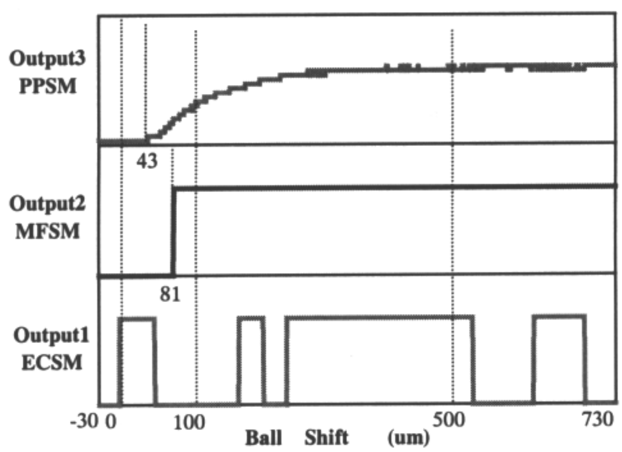

Fig. 12 Experimental result of the evaluation of sensing methods

make the pneumatic ball probe with high resolution and miniature stylus.

5.2 Evaluation of Sensing Methods[3]

After we found the optimized size of pipeline conditions for pneumatic ball probe, we consider the three methods for sensing system. There are "electric conduction sensing method", "mechanical flux sensing method", and "pneumatic pressure sensing method", see Fig. 11.

- Electric conduction sensing method (ECSM)
  We connect stylus pipe to high voltage (+5Volt.) and moving stage series with a resistance to ground. Because of making pipe, ball, and moving stage of conductor, when we move the stage touching to the ball, it is a close loop from pipe to stage. At the same time, it changes output1 from low voltage to high voltage.
- Mechanical flux sensing method (MFSM)
  Because of the shift of probe ball, the air flows into probe. When the airflow is strong enough to push the indicative ball up of light-trap sensor. It changes the signal of output 2 from low to high.
- Pneumatic pressure sensing method (PPSM)
  Because of the shift of probe ball, the air flows into probe. It changes the vacuum pressure inside of probe. We detected the change of pressure with pressure sensor as output 3.

We moved the moving stage for 1 μm per step, and recorded the output signals of all 3 sensors at every step position of moving stage. From Fig. 12, we know that ECSM is the fastest one that detected the touch of probe, but it is most unstable because of the vibration of ball caused by airflow. PPSM is 2nd faster than MFSM, but it is also a little unstable to detect and needs a much biggest space to place the pressure sensor. Although MFSM has the longest none reaction distance, we can revise it by calibration. However, considering about the stability of sensor and the miniaturization of probe, we choose "Mechanical flux sensing method" as the sensing method of pneumatic ball probe.

5.3 Evaluation of Measuring Force[4]

For measuring such a tiny measuring force of pneumatic ball probe, we make a micro measuring force equipment (see **Fig. 13**) that can measure the force at 0.1 mN order. This equipment is composed of a board 0.1mm thick as a

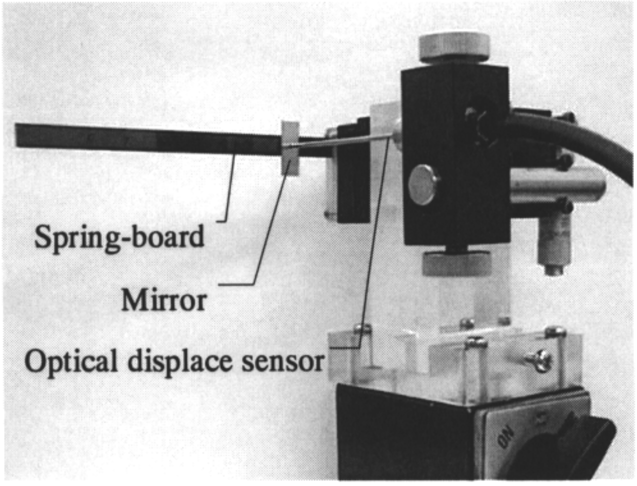

Fig. 13 Micro measuring force equipment

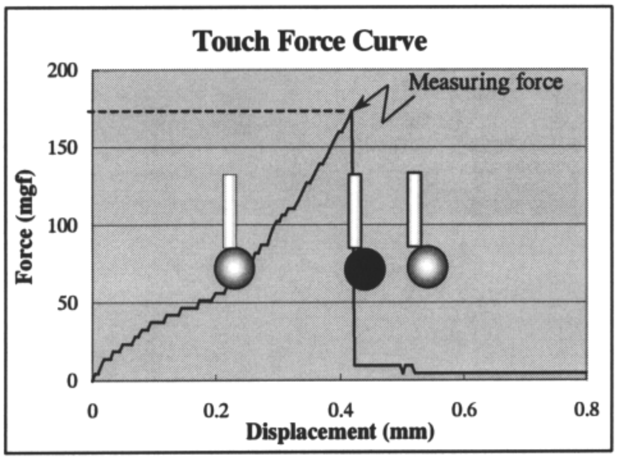

Fig. 14 An example of the change of touch-force in the process of probing

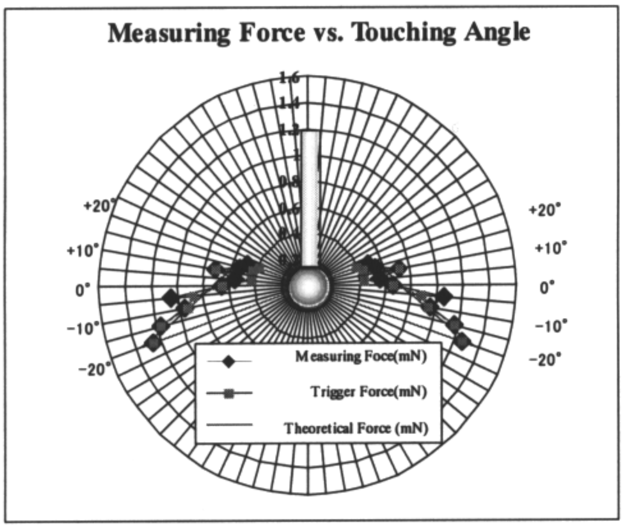

Fig. 15 Touch-force vs. touch angle for measuring force, trigger force, and theoretical force at probe ball ϕ2 mm, pipe inner diameter 0.4 mm

spring, a small mirror, and an optical displace sensor. When probe touches to the leaf spring, the bending quantity of board can be measured by the optical displace sensor and converts to force.

Fig. 14, an example of experimental results, shows the change of touch-force in the process of probing. From it, we knew that touch-force is getting larger and larger from the touch-point. At one point, as it increases enough, the force rapidly decreases down when probe ball shift away from center of pipe tip. The touch-force before rapidly decreasing down is the measuring force of probe, because it is the force that makes probe ball shift away from center of pipe tip.

We measured the measuring forces using ϕ 1 mm and ϕ 2 mm probe balls are 0.193 mN and 0.096 mN, respectively. The effect of touch-angle to measuring force is illustrated in Fig. 15.

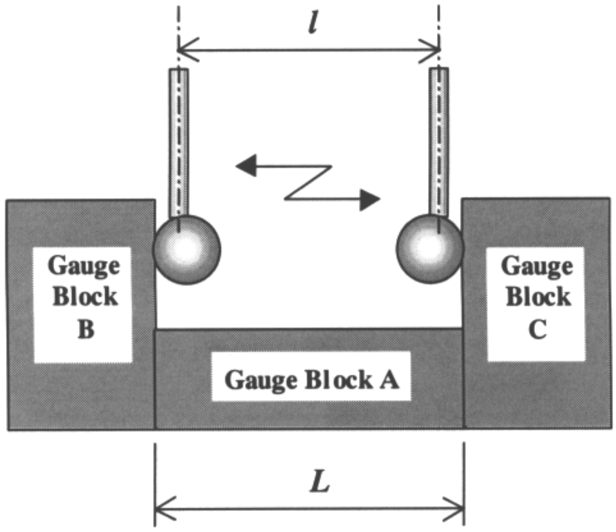

Fig. 16 The structure of groove gauge

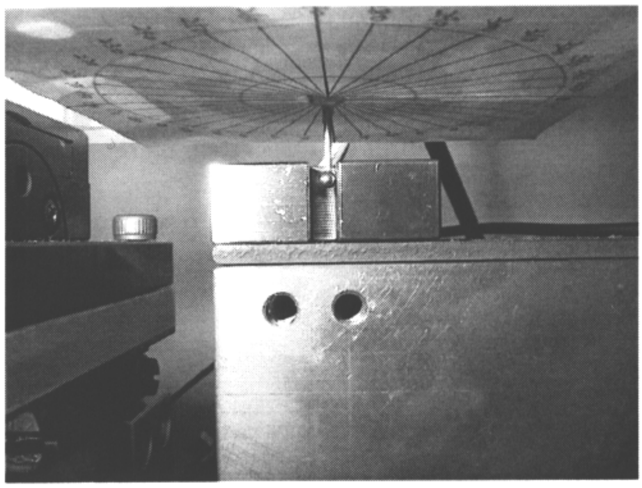

Fig. 17 Groove gauge for evaluating accuracy of pneumatic ball probe

5.4 Evaluation of Accuracy

Both **Fig. 16** and Fig. 17 show the equipment that we evaluated the accuracy of prototype. This equipment is composed of 3 gauge blocks. Gauge A is putted between gauge B and C to use like a groove gauge. We used it to evaluate the accuracy of repeatability and effective radius.

We move the probe to touch one side of gauge block until the probe triggered, record the position of trigger point and move the probe back to starting point. Repeat the process above for 10 times using ϕ 1 mm and ϕ 2 mm probe balls. The standard deviation of repeatability for using ϕ 1 mm probe ball is 1.1 μm and for using ϕ 2 mm probe ball is 1.8 μm, respectively.

We also move the probe right and left to touch the blocks C and B for measuring groove distance as l. However the true distance of groove L is the length of gauge block A, so we can calculate the effective radius from equation (11).

$$r' = \frac{L - l}{2} \qquad (11)$$

The effective radiuses are 0.483 mm and 0.970 mm for using ϕ 1 mm and ϕ 2 mm probe balls, respectively.

6. Conclusion

For using low measuring force to measure the soft materials (like plastics etc.), we submitted this novel structure which separates probe ball from stylus pipe, using vacuum pressure to hold them together. According to the theoretical analysis, we estimate the design specifications and measuring force of pneumatic ball probe. Furthermore, we made some fundamental experiments and evaluating experiment of sensing methods to verify the sensing theory and find the optimized specifications of pipeline and a stable, miniaturizable sensing method for this probe.

Then we made a prototype of pneumatic ball probe according to the results of fundamental evaluation and evaluation of sensing methods. We use this prototype probe to evaluate the measuring force and accuracy of pneumatic ball probe.

As the results of experiments showed in section 5.3, we got the experimental result of minimum measuring force 0.0964 mN at using a probe ball of ϕ 2 mm. This probe can easily make the measuring force smaller than 1 mN.

From the results of evaluation of accuracy, we got the best standard deviation of repeatability is 1.1 μm at using a probe ball of ϕ 1 mm.

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