Theoretical and Experimental Studies of a Novel Cone-Jet Sensor

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***Abstract*—Modeling of a novel cone-jet sensor using two-dimensional (2-D) finite element analysis was investigated for dimensional measurement. Theoretical and experimental studies demonstrated that a cone-jet sensor supplied with air can be used to accurately measure displacement, and its work range of 1.5 to 4.2 mm is some ten times greater than a simple back-pressure sensor. It is anticipated that this type of sensor will find wide applications in manufacturing industry due to its wider working range, high precision, and other features.**

***Index Terms*—Boundary condition and clearance, cone-jet sensor, finite element analysis, velocity.**

I. Introduction

An AIR gauging sensor is noncontacting and has the advantage that the air flow through the measurement orifice keeps the part surface clean, making the sensor insensitive to effects of coolant and thus an excellent device for in-process machining measurement. The back-pressure principle has been well established in metrology as a means of measuring small dimensional variations. Despite its success in post-process inspection, its use as an in-process-measuring device is somewhat restricted because of its rather limited linear operating range. The cone-jet sensor has been employed in industrial applications [1] and is now being further investigated [2]. Due to its complex configuration, it is rather difficult to establish its theoretical model and obtain the analytical solution. To solve this problem, the two-dimensional (2-D) finite element method has been used to optimize the configuration of the cone-jet sensor [3], [4]. A cone-jet sensor optimized is shown in Fig. 1. In this paper, the relationship between the sensor output pressure and the measured displacement or clearance will be analyzed using the 2-D finite element method, and the characteristics will be compared with the experimental results.

II. Theory and Methods

If the inlet circular tube, as shown in Fig. 1, is considered as a part of the sensor to be modeled using FEA, the 2-D model becomes very complicated. Without the inlet circular tube, the cone-jet sensor can be redrawn as Fig. 2. This has been used to approximate the model given in Fig. 2. Since the FEA software can only use velocities as boundary conditions, all boundary conditions have to be converted to velocities. In the experiment, the input air flow can be measured by a flow meter and the average velocity calculated. There exist laminar and turbulent flows in both the annuli and circular tube. While it is also possible to derive the theoretical equations for the laminar flows, it is very difficult to analyze the turbulent flows and to predict the general velocity distribution in annuli. The geometry of the annulus makes all velocity equations considerably more complicated.

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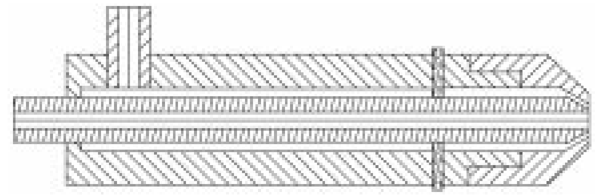

Fig. 1. Diagrammatic representation of a cone-jet sensor.

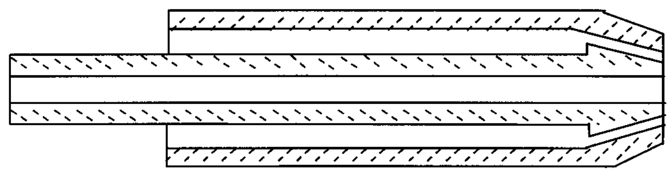

Fig. 2. Sectional view of modified cone-jet sensor.

Shown in Fig. 3 is a cross section of the annulus consisting of an outer tube with an inside diameter d_2 and an inner tube with an outside diameter d_1. Their radii are r_2 and r_1, respectively. The air flow input to the cone-jet sensor and the average velocity in the annuli can be calculated as follows

$$\overline{v} = \frac{Q}{\pi\left[(d_2/2)^2 - (d_1/2)^2\right]} \tag{1}$$

where Q is the air flow.

By substituting the values of Q, d_1, and d_2 into (1), the average velocity can be obtained:

$$\overline{v} = 9.95 \quad \text{m/s.}$$

The cross section of the inlet of the cone-jet sensor is shown in Fig. 4. According to the definition of the hydraulic radius, it can be calculated as follows:

$$R_h = \frac{A}{P} = \frac{\pi(r_2^2 - r_1^2)}{\pi(2r_2 + 2r_1)} = \frac{r_2 - r_1}{2} \tag{2}$$

where A is the cross-sectional area of the flowing fluid and P is the wetted perimeter, that portion of the perimeter of the cross section where there is contact with fluid. In evaluating the

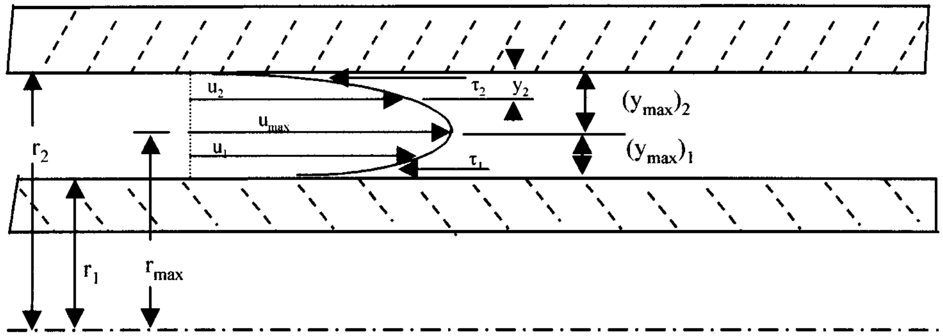

Fig. 3. Cross section of plain annuli.

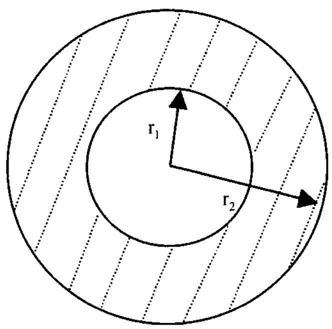

Fig. 4. Cross section of annular space.

Reynolds number for flow in annuli, it is customary to substitute $4R_h$ for D in (3)

$$\mathrm{Re} = \frac{VD\rho}{\mu}. \tag{3}$$

The gaseous medium is air, its density $\rho = 1.293$ kgm^{-3}, viscosity $\eta = 18.325$ Pa-s, and average velocity $\overline{v} = 9.95$ m/s, so the Reynolds Number can be calculated as

$$\mathrm{Re} = \frac{2V(r_2 - r_1)\rho}{\mu} = 2.808 \times 10^3.$$

Since the Reynolds number is over 2000, the air flow in annuli is turbulent flow. Although very few studies have been carried out on the turbulent velocity profiles in annuli, Rothfus determined point velocities for turbulent air flows in two different annuli [6]. Knudsen and Katz have also determined velocity profiles in an annulus for water flow. At some point between the two walls of the annulus, the point velocity reaches a maximum value. The turbulent velocity profile is very flat in the vicinity of the maximum velocity, and the determination of $r_{\max}$ experimentally is quite difficult. The value of $r_{\max}$ is determined in terms of r_1 and r_2. Equation (4) may be used to predict the approximate point of maximum velocity in turbulent velocity profiles in annuli [6]

$$r_{\max} = \sqrt{\frac{r_2^2 - r_1^2}{2\,\ln(r_2/r_1)}}. \tag{4}$$

The values of r_2 and r_1 are substituted into (4), and $r_{\max}$ can be calculated

$$r_{\max} = 4.97 \text{ mm}.$$

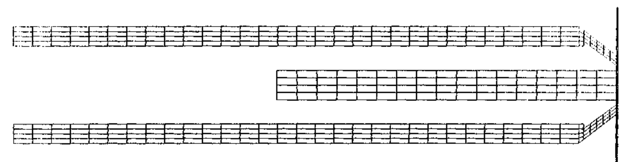

Fig. 5. Two dimensional meshed model of cone-jet sensor.

Since the value of $r_{\max}$ does not correspond to the midpoint in the annulus, it is necessary to divide the velocity profile into two parts, the outer portion extending from the outer tube wall to the point of maximum velocity, and the inner portion extending from the point of maximum velocity to the wall of the inner tube. Bailey [7] investigated the data of Knudsen and Katz, and reported that the following relationships hold within experimental error for the inner and outer velocity profiles, respectively

$$u_2 = 1.14 \cdot \overline{v}\left(\frac{r_2 - r}{r_2 - r_{\max}}\right)^{0.142} \qquad (r_{\max} \le r < r_2) \tag{5}$$

and

$$u_1 = 1.14 \cdot \overline{v}\left(\frac{r - r_1}{r_{\max} - r_1}\right)^{0.102} \qquad (r_1 < r \le r_{\max}) \tag{6}$$

where $\overline{\nu}$ is the average velocity. From (5) and (6), the velocities in the inlet of the cone-jet sensor as the boundary conditions can be calculated after the air flow is measured.

III. Modeling

In designing cone-jet sensors, finite-element flow analysis is one of the best tools for a better understanding of various phenomena. However, because of their complex structures and the presence of a gap, meshing is quite difficult and the number of elements becomes very large when trying to solve in three dimensions. Therefore, a 2-D axisymmetric elements method is often used, since these elements are useful for flow situations where the flow is symmetric about an axis, especially for turbulent flow, which can easily become divergent for three-dimensional finite element analysis.

A 2-D meshed model of the cone-jet sensor is shown in Fig. 5, and the stagnant region is shorter than the practical one to decrease the number of mesh cells and simplify the calculation. It is based on the fact that the change will not influence the output pressure in the stagnant region. With the clearance between the nozzle and the measured object in the range 0.2 mm to 4.5 mm,

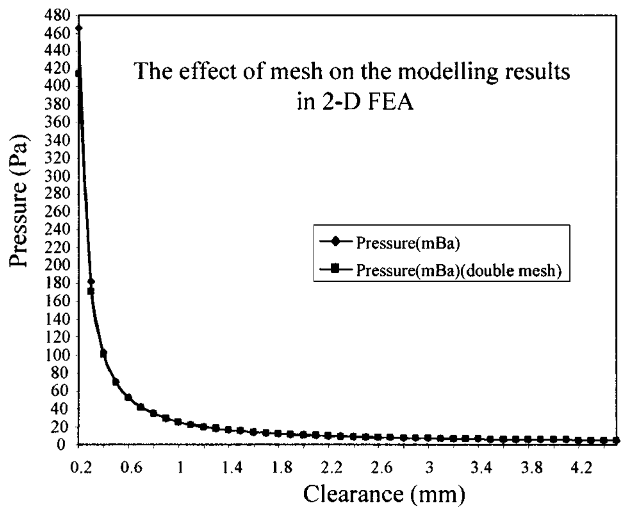

Fig. 6. Modeled results in the range of 0.2 to 4.5 mm.

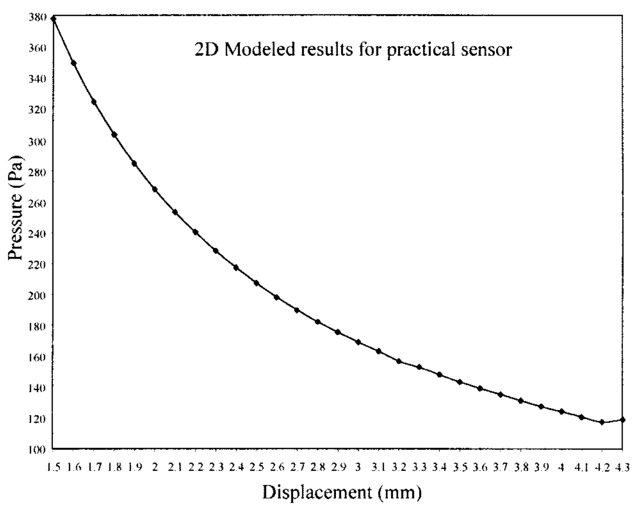

Fig. 7. Modeled results in the range of 1.5 to 4.3 mm.

a series of corresponding models were analyzed using finite element analysis. With the clearance in the same range, the models with double meshes were also analyzed, and the results were compared.

The modeled results in the range of 0.2 to 4.5 mm are shown in Fig. 6. It has shown that the two modeled results are nearly the same and about 1% different, which indicated that the meshes are enough for the calculation. The modeled results also showed that the output pressure decreases abruptly with increasing clearance when the clearance is changed from 0.2 to 1.4 mm and after that, the pressure decreases slowly. This means the sensor may be operated in two working ranges. The second working range is investigated in this paper in order to achieve a wider working range. It can be seen that the output pressure evenly decreases with increasing clearance over a range of 1.5 to 4.5 mm, as shown in Fig. 7, and is approximately linear over this range.

IV. Experimental Results

The experimental setup is shown in Fig. 8. During the experiment, the air source was supplied by a compressing machine and

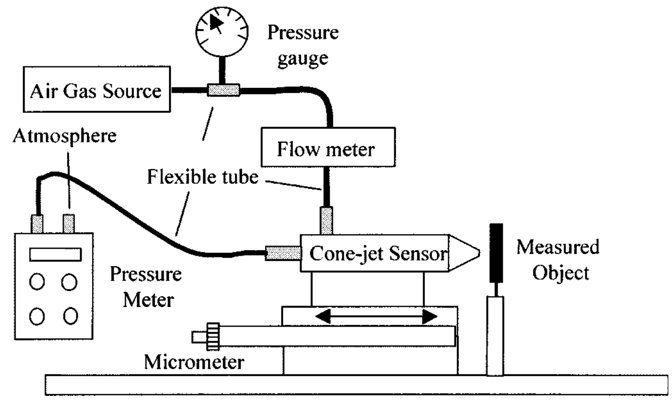

Fig. 8. Experimental setup.

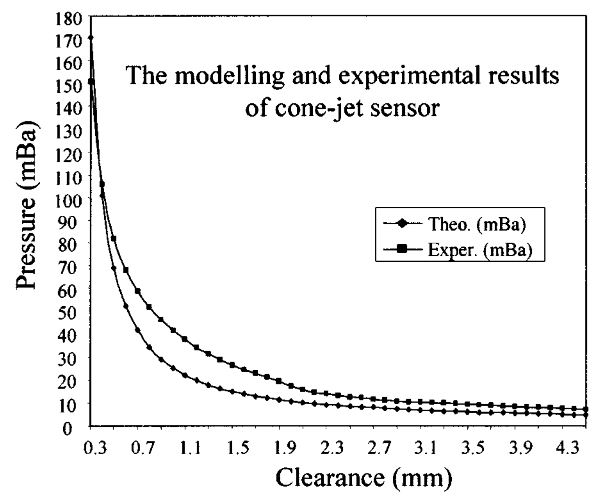

Fig. 9. Modeling and experimental results with clearance in the range of 0.3 to 4.5 mm.

processed and controlled by a pneumatic filter and regulator. The pneumatic filter and the regulator were respectively used for removing water vapor and impurities from the air supply and adjusting the air supply pressure. The air flow was measured and monitored by an air flow meter. The cone-jet sensor was mounted on the same guide track as the measured object to align them on the same axis when the sensor was moved to or from the measured object. The measured object is a mirror with the size of 20 mm $\times$ 20 mm. The sensor was positioned normal to the measured surface and adjusted to change the clearance by a micro-adjustment with the resolution of 5 μm. The sensor output pressure at the center of the stagnant region of the cone-jet sensor was measured using a differential pressure meter with the resolution of 0.1 mbar in the range of 0 to 300 mbar. Since the pressure is over the measuring range of the pressure meter when the clearance is 0.2 mm, the measured clearance started from 0.3 mm in the experiment. The modeling and experimental results in the working range of 0.3 to 4.5 mm are shown in Fig. 9. The experimental results with clearance in the range of 1.5 to 4.5 mm are shown in Fig. 10.

V. Discussion and Conclusions

Comparing the modeling results with experimental results, the relationships between the output pressure and measured dis-

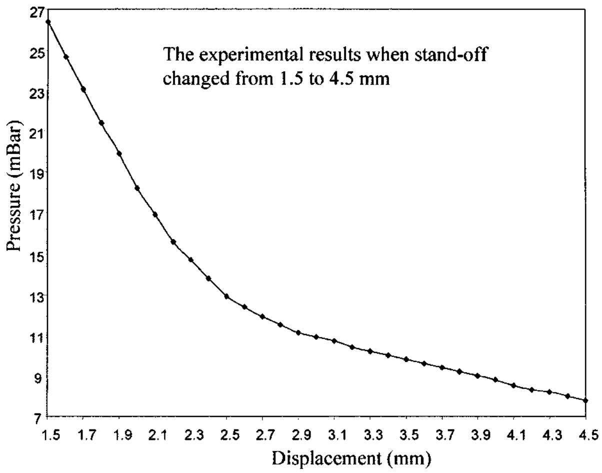

Fig. 10. Experimental results when clearance in the range of 1.5 to 4.5 mm.

placement present similar changes, but the experimental output pressure is a little higher than the modeled one for the same clearance when the clearance is above 0.5 mm. This is due to 2-D finite-element approximation, meshing selection, and experimental errors. It is shown that the characteristic is approximately linear over a range of 1.5 mm to 4.5 mm, which can be used as the working range.

The experiment has shown that the pressure in the stagnant region of the cone-jet sensor is a function of the clearance between the nozzle and the surface of the measured object. Although the absolute output pressures of the cone-jet sensor using the 2-D finite element analysis are smaller than the experimental values, the relationship between the output pressure and the clearance appears to be similar. The experimental results indicated that the 2-D model has provided important references in the design of a cone-jet sensor. Both the preliminary modeling and the experimental results have shown that the cone-jet sensor has a much wider working range proximately than the back-pressure sensor [6]. It is anticipated that this type of sensor will find wide applications in the manufacturing industry due to its wider working range.

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