Curved Measurement Theory of Honing Pneumatic Measurement System and Optimization of Measurement Parameters

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Abstract. In the previous research on dynamic process of honing pneumatic measurement system are studied by measuring plane measurement instead of the surface, but to achieve high-precision measurement of aerodynamic honing, instead of surface measurement by plane measurement is not scientific. Based on the study of the theoretical basis of pneumatic measurement and air dynamics, through the dynamic study of nozzle baffle mechanism in the measuring system of gas honing, studies have shown that the measurement accuracy is higher than the baffle surface characteristic equation characteristic equation of plane baffle. Using this characteristic equation, the design of gas momentum meter and measurement system is more accurate, and it provides a reliable reference for improving the measurement accuracy of honing pneumatic measurement. For the equation of curved baffle property verification and optimization of the parameters of the nozzle, based on the entity model, gas path structure and nozzle of gas measuring device of dynamic curved baffle FLUENT software simulated. The simulation results show that the air flow changes during the operation of the pneumatic measuring device, and the pressure values are obtained. The pressure clearance curve of the curved baffle is plotted by drawing software, and the correctness of the characteristic equation of the surface baffle is verified by comparing with the theoretical curve. By adjusting the model parameters, the pressure clearance curves of different main and measuring nozzle apertures are obtained by repeated simulation. Then the law is found according to the results and the parameter design is optimized.

1. Introduction
In recent years, honing has become an indispensable process technology for precise coupling parts [1-3] such as engine cylinder sleeve, cylinder bore, and important hydraulic cylinders in construction machinery. Honing is finishing and finishing grinding method on the surface of the work piece, the advantages of high precision honing is safe, economic, reliable, durable and efficient, is widely used in machining of cylinder, cylinder, piston rod, pin hole, hole pump cylinder hole, hydraulic valve hole,
bearing hole and bearing etc. [1]. The traditional honing process adopts the repeated process of "processing, cutting back, measuring and reprocessing", and its size measurement is usually measured manually by off-line manual measurement. The measurement accuracy and efficiency are relatively low. Applying on-line pneumatic measurement technology to bore size measurement of bore hole, it can improve production efficiency and realize automation of inner whole honing process.

The online measurement of the non-contact type pneumatic measuring technology [4-7] is introduced into the hole honing aperture size, the gas electric conversion module in real time will be in transition pore size change for the aperture signal, then the signal is processed to display and control system for subsequent analysis and control [8-9], which is helpful to the numerical control loop hole honing machine of high precision processing control.

With the further research of engine operation mechanism in engineering field, higher requirement of honing accuracy is put forward. The accuracy of honing machine determines the machining accuracy of honing machine. At present, pneumatic measurement is widely used in honing system. Lanzhou University of technology, Lanzhou Industry and Equipment Co. Ltd Zhang Wanjun et al researchers [15-21] have researched interpolation algorithms for NURBS curves honing pneumatic measurement system. Here has been attempts to change the feed rate in NURBS interpolation honing pneumatic measurement system.

In the past research process of honing pneumatic measurement system, plane measurement was used instead of surface measurement. The design of measurement parameters mainly adopts empirical estimation and experimental comparison method. However, it is not scientific to use the plane measurement instead of the surface measurement to achieve the high precision of the honing pneumatic measurement. Therefore, it is necessary to study the theory of surface measurement and the optimization of measurement parameters. So, the subject of honing pneumatic measurement system in the surface measurement theory and optimization of measurement parameters, to achieve high-precision honing pneumatic measurement, in order to meet the requirements of high-precision honing processing.

The parameter design of the traditional gas momentum instrument mainly adopts the method of empirical estimation and experimental comparison. Based on the theoretical research of aerodynamics and fluid mechanics, a theoretical model for parameter design of honing gas momentum meter is established. By computer simulation, the design parameters of the gas momentum meter are further optimized. The design of the pneumatic measurement system is guided in theory, so that the pneumatic measurement can be better applied to machinery and various industries.

2. Aerodynamic measurement model
The basic principle of pneumatic measurement is introduced with pneumatic back pressure pneumatic measuring system, and the schematic diagram is shown in Fig.1.
Compressed air from the air filter 1 by 2 by 3 after the filter inlet valve into the regulator regulator 4, subsequent gas path pressure stabilized at $p_c$. Compressed air of pressure $p_c$ flows through the orifice 5 toward the measuring head (usually the nozzle flapper mechanism) and flows from the probe into the atmosphere. The pressure $p_c$ in the pipe section between the orifice 5 and the pneumatic measuring head is called back pressure.

3. Calculation of equivalent clearance of curved nozzle flapper mechanism

When the back pressure $p_i$ gradually drops from $p_c$ to $p_i \geq 0.0894 MPa$; the main nozzle is subcritical under the condition III, and the gas flow velocity at the baffle is in a critical state. According to fluid dynamics knowledge, the flow rate $g_1$ through the main nozzle and flow through the baffle are $g_2$, respectively:

\[
Q = cF \sqrt{2g \frac{n}{n-1} p_i \gamma_i \left(\frac{P_2}{P_1}\right)^\frac{2}{n} - \left(\frac{P_2}{P_1}\right)^\frac{n+1}{n}}
\]

Type: $Q$ - weight flow through the cross section, Kg/s;
- $c$—discharge coefficient;
- $F$—Flow area of nozzle, m$^2$;
- $n$—Constant entropy coefficient, For air, $n=1.4$;
- $g$—Gravitational acceleration, $g=9.81$ m/S$^2$;
- $P_1$—Absolute pressure at the front of the nozzle, kpa;
- $P_2$—Absolute pressure behind the nozzle, palmer;
- $\gamma_i$—$P_1$ Gas gravity under.

When the flow state of the gas passing through the nozzle is in the subcritical state, i.e. $p_2/p_1 \geq 1.894$, the flow rate is expressed as:

\[
Q = cF \left(\frac{2}{n+1}\right)^\frac{1}{n+1} \sqrt{2g \frac{n}{n+1} p_i \gamma_i}
\]

Supposed

\[
Q = K_i F
\]

The flow of gas through the nozzle is in a subcritical state,

\[
K_i = c \sqrt{2g \frac{n}{n-1} P_i \gamma_i \left(\frac{P_2}{P_1}\right)^\frac{2}{n} - \left(\frac{P_2}{P_1}\right)^\frac{n+1}{n}}
\]

When the flow of gas through the nozzle is in a critical state,
The formula 4 or formula 5 is substituted formula 6, and the order $K$ is obtained

$$G = KdS$$

As shown in Fig.2, the nozzle bore diameter is $d$, the outer diameter of the nozzle is $d_2$, and the end face is flat. The bezel is a circular cylinder with a radius of $R$. The relative position of the nozzle and the baffle is the axis of the nozzle hole intersecting the axis of the round cylinder, and the axis of the cylinder is parallel to the end face of the nozzle. The maximum distance from the end face of the nozzle to the inner surface of the cylinder is a gap $S$. It is obvious that when the clearance $S$ is determined, the flow rate $Q$ is not equal to $KdS$.

Supposed, relationship between $Q$ and $S$ for the gap flow

$$Q = KdS - G_R$$

Then, the clearance $S_R$ of the parallel plane nozzle flapper mechanism with a nozzle diameter of $D$ is called the clearance clearance of the curved baffle mechanism when the flow rate is $G_R$

$$G_R = KdS_R$$

So,
The equivalent clearance $S_R$ is an important parameter for designing an air momentum meter. When the $S$ is determined, the difference between the surface area of the flat baffle and the curved baffle is $F_R$, as shown in Fig. 5,

$$AB = OO' - OC = R - \sqrt{R^2 - BC^2} = R - \sqrt{R^2 - AO^2}$$  \hspace{1cm} (10)

Because the surface baffle is a cylinder block, the $AO'$ is $AO''$ on different cross sections. If the nozzle radius is $r$, then

$$AO'' = O'A' \sin \theta = r \sin \theta$$  \hspace{1cm} (11)

Outflow area of $F_R$ for any projection in the plane of the circular baffle nozzle diameter on a $A'$ to $A'B'$ curved baffle distance $rd \theta$ and length of product in $\theta$ from $0$ to $2\pi$ points, i.e.

$$A'B' = R - \sqrt{R^2 - r^2 \sin^2 \theta}$$  \hspace{1cm} (12)

The formula (12) is substituted (13)

Instant,

$$F_R = \int_0^{2\pi} \left( R - \sqrt{R^2 - r^2 \sin^2 \theta} \right) rd \theta$$  \hspace{1cm} (13)

In accordance with the definition of equivalent clearance, $S_R = \frac{F_R}{\pi d}$, so

$$S_R = \frac{r^2}{4R} = \frac{d^2}{8D}$$  \hspace{1cm} (14)

Therefore, when the flow state of the gas passing through the nozzle is in the subcritical state, that is $\frac{p_2}{p_1} < 1.894$, the flow rate of the surface baffle is:

$$Q = c \pi d \sqrt{2g \frac{n}{n-1} P_{ri} \left( \left( \frac{P_2}{P_1} \right)^{\frac{2}{n}} - \left( \frac{P_2}{P_1} \right)^{\frac{n+1}{n}} \right) \left( S - \frac{d^2}{8D} \right)}$$  \hspace{1cm} (15)

The characteristic equations of the plane baffle measurement system under four operating conditions are [13]:

Condition I:
\[
\begin{align*}
P_x &= P_e - \frac{P_e \left( \frac{P_a}{P_e} \right)^{\frac{2}{n}} \left( \frac{P_a}{P_e} \right)^{\frac{n-1}{n}} \left[ c_1 d \left( \frac{d_1}{4} \right) \right]^2}{n-1 + \frac{2n-2}{n} \left( \frac{P_a}{P_e} \right)^{\frac{2}{n}} - \frac{n-1}{n} \left( \frac{P_a}{P_e} \right)^{\frac{n-1}{n}} \left[ c_1 d \left( \frac{d_1}{4} \right) \right]^2} \tag{16}
\end{align*}
\]

Condition II:

\[
\begin{align*}
P_x &= \left[ \frac{1}{2} P_0^{\frac{n-1}{n}} + \frac{1}{2} \left( P_0^{\frac{2n-2}{n}} + 4P_0^{\frac{2}{n}} B^2 P^2 \left( A^2 S'^2 \right)^{\frac{1}{2}} \right) \right]^{\frac{1}{n-1}} \tag{17}
\end{align*}
\]

Condition III:

\[
\begin{align*}
P_x &= P_e \left[ 0.5 + 0.5 \left( 1 + 4 \frac{A^2}{B^2} S'^2 \right)^{0.5} \right]^{\frac{n}{1-n}} \tag{18}
\end{align*}
\]

Condition IV:

\[
\begin{align*}
P_x &= \frac{c_1 d_1^2}{4c_1 d S'} \frac{c_1 d_1^2}{4} \tag{19}
\end{align*}
\]

Where, \( S' \) is the measuring clearance.

- \( C_1 \) — The flow coefficient at the orifice (main nozzle);
- \( d_1 \) — Orifice diameter;
- \( P_e \) — work pressure (absolute pressure);
- \( P_x \) —back pressure (absolute pressure);
- \( n \) - The constant entropy index, for air;
- \( \gamma_e \) — \( P_e \) under the severe gas.

By comparing with the equation of curved baffle measurement system characteristics, we can draw in the measuring chamber pressure \( P_x \) and other parameters of the nozzle under the same measuring clearance error measuring gap curved baffle and plane baffle is \( \frac{d^2}{8D} \), the measurement accuracy is calculated according to the curved baffle characteristic equation characteristic equation of \( \frac{d^2}{8D} \) is higher than the plane baffle.
According to the requirements of this project, the accuracy of honing aerodynamic measurement is 1 μm. When the \( D \geq 125d^2 \) is available, it is necessary to study the characteristic equation of the surface baffle, instead of the characteristic equation of the plane baffle. When \( D \geq 125d^2 \) is used, the characteristic equation of the plane baffle can be used to approximate the characteristic equation of the curved baffle.

According to whether the flow velocity of the main nozzle and the measuring nozzle is in a critical state, the working conditions of the gas momentum instrument can be divided into four working conditions types, as shown in Fig. 3:

![Figure 3. Working area diagram of air momentum instrument](image)

The lines A, B and C intersect into four zones, i.e., II, III and IV respectively, which are the four conditions of back pressure meter, corresponding to the four working conditions listed in table 3.1.

The influence of the characteristic equation of the curved baffle and the characteristic equation of the baffle plate on the measurement accuracy is analyzed and compared. It is shown that the measurement accuracy of the characteristic equation of the curved baffle is higher than that of the planar baffle, and the accuracy is \( \frac{d^2}{8D} \). When the honing accuracy is m 1 m and \( D < 125d^2 \), the influence of the diameter of the curved baffle on the measurement accuracy must be considered. The characteristic equation of the baffle cannot be used to study the characteristic equation of the curved baffle.

4. Feeding method of honing fluid

The honing fluid flows downward along the axis of the honing head in the annular narrow slot between the inner wall of the workpiece and the grinding head, which can be approximately viewed as a concentric cylindrical annular gap flow. As the hydraulic diameter of the gap (relative to the diameter of the circular section) is very small, as the working fluid honing fluid has a certain viscosity, honing fluid flow in the gap when the Reynolds number is small, generally belong to laminar flow range. The mechanism of honing liquid annular gap in motion has two: one is the flow due to the pressure difference, this flow is called flow differential pressure; the other is due to the composition of gap wall with relative motion (i.e. honing head movement) and the liquid flow in the gap, known as shear flow, the superposition of the two is called the pressure difference shear flow. The differential pressure flow is the dominant flow mode.

As shown in Fig. 4, the gap height is:
\[ \delta = \frac{D_2 - D_1}{2} \]  

(20)

\( D_2 \) - workpiece bore diameter; \( D_1 \) - grinding head; \( \delta \) - symmetrical baffle spacing.

As the gap size \( \delta \) is small, the concentric cylindrical annular slot flow can be approximately regarded as a parallel plate gap flow with a width of \( b = \pi D_1 \), as shown in Fig. 5.

**Figure 4.** Gap flow between parallel plates

**Figure 5.** Mesh diagram of a cross-section of a rotating shaft

**Figure 6.** Total pressure inlet diagram

**Figure 7.** Total pressure exit diagram
We use Flunt to make Fig.6, Fig.7 and Fig.8, the correctness of the characteristic equation of the surface baffle is validated by the fluid simulation software FLUENT. The simulation results of FLUENT software are used to draw the $P_x-S$ (back pressure clearance) curve, and compare with the theoretical equation curve. It proves that the characteristic equation of the surface baffle is correct. The simulation results show that the air flow changes during the operation of the pneumatic measuring device.

5. **Experiment simulation and analysis**

In our laboratory, the main nozzle, measuring nozzle experimental data diagram, Simulation, curve, of, NC, honing, machine diagram, as shown in Fig.9, the nozzle and measuring nozzle experimental data are shown in Fig.10 and Fig.11, respectively:

The overall design of the project adopts high-pressure differential pressure pneumatic measurement method, and the signal pickup and conversion process is as follows:

1. The clearance $S$ between the probe and the curved baffle is converted to the back pressure of the air chamber $P_x$;
2. Use a piezoresistive pressure converter to convert the back pressure $P_x$ into current value $I$ output;
3. The regulating circuit converts the current parameter $I$, which is output by the pressure converter, to voltage parameter $U$;
4. The 16 bit conversion precision A/D converter quantifies analog voltage values into binary digital values; the binary voltage value acquired by the computer is converted to the actual voltage value;
(5) After measuring the gap voltage to the gap value, the gap value is compared with the measuring inductance of the inductance micrometer used as calibration, and the corresponding gap value is obtained;

(6) Display measurement results.

Source provided by air compressor, pressure is 104~106Pa, with links to the high pressure gas source to remove moisture, oil droplets and solid particles, the use of precision gas regulator to link voltage stable pressure 0.2MPa in the pressure of work. The gas after the pressure adjustment goes to the measuring nozzle and picks up the measuring signal. A/D conversion data acquisition card will collect the binary voltage value to the computer, the computer processing to obtain surface measurement parameters and display output.

(1).Main nozzle

We will measure the nozzle diameter was 0.4mm and the entrance pressure of 0.2MPa (g), the main nozzle simulation in different aperture of the pressure values are listed in Tab.1.

**Table 1. Pressure (P_x/P_a) comparison tables for three main nozzle models**

| clearanceS/mm | Outside diameter of main nozzle d_x/mm | 0.2     | 0.4     | 0.6     |
|--------------|--------------------------------------|---------|---------|---------|
| 0            | 199998                               | 199989  | 199998  |
| 0.005        | 50522                                | 183478  | 196597  |
| 0.100        | 31                                   | 142474  | 186745  |
| 0.150        | —                                    | 94012   | 171588  |
| 0.200        | —                                    | 54555   | 156012  |
| 0.250        | —                                    | 34670   | 134071  |
| 0.300        | —                                    | 23884   | 129498  |
| 0.350        | —                                    | 17463   | 93040   |
| 0.400        | —                                    | 13330   | 70182   |
| 0.450        | —                                    | 10508   | 54880   |
| 0.500        | —                                    | 8498    | 44126   |
| 0.550        | —                                    | 7015    | 36263   |
| 0.600        | —                                    | 5892    | 30342   |

Draw the pressure value shown in Tab.1 as the corresponding P_x-S curve, as shown in Fig.10.

![Figure 10. Performance comparison of three models of main nozzle](image-url)
1. \( d_1 = 0.2 \text{mm} \) II: \( d_1 = 0.4 \text{mm} \) III: \( d_1 = 0.6 \text{mm} \)

Figure 10. Is a diagram of the clearance - back pressure gas path drawn to change the bore diameter of the main nozzle. You can see from Fig.10:

1. With the increase of the bore diameter of the main nozzle, the amplification factor (the slope of the straight line) of the pneumatic conversion section decreases;
2. As the diameter of the main nozzle increases, the viscous part of the curve increases;
3. As the diameter of the main nozzle increases, the linear part in the middle of the curve increases.

These results suggest that measuring gap initial and maximum measuring gap size can be increased due to increase of main nozzle pneumatic instrument, fixed in the case of measuring nozzle can also by fine-tuning the main nozzle aperture to change the magnification of gas dynamic link with the need to transform the pneumatic measuring instrument overall magnification.

6. Measuring nozzle

The main nozzle bore diameter is 0.4mm, the inlet pressure is 0.2MPa. The pressure value of the nozzle under different aperture is measured in Tab.2.

| clearance S/mm | measuring nozzle bore \( d \)/mm |
|---------------|-----------------------------|
| 0.2           | 0.4                        | 0.6                        |
| 0             | 199999                     | 199999                     | 199999                     |
| 0.05          | 195671                     | 183479                     | 165461                     |
| 0.1           | 183354                     | 142471                     | 94569                      |
| 0.15          | 164780                     | 94019                      | 31453                      |
| 0.2           | 145011                     | 54556                      | 23995                      |
| 0.25          | 148819                     | 34670                      | 15241                      |
| 0.3           | 100423                     | 23885                      | 10533                      |
| 0.35          | 72469                      | 17465                      | 7721                       |
| 0.4           | 54829                      | 13328                      | 5908                       |
| 0.45          | 42969                      | 10508                      | 4661                       |
| 0.5           | 34611                      | 8499                       | 3772                       |
| 0.55          | 28477                      | 7016                       | 3135                       |
| 0.6           | 23849                      | 5891                       | 261                        |

The pressure values shown in Tab. 2 are plotted as corresponding Px-S curves, as shown in Fig.11.
Figure 11. Performance comparison of three models for measuring nozzles

Ⅰ: $d = 0.22 \text{mm}$ Ⅱ: $d = 0.42 \text{mm}$ Ⅲ: $d = 0.62 \text{mm}$

Fig.11 is a change in the diameter of the measuring nozzle bore clearance - back pressure gas path characteristics diagram. You can see from Fig.11:

1. As the diameter of the nozzle increases, the amplification (slope of the straight line) of the pneumatic conversion section increases;
2. As the diameter of the nozzle increases, the viscosity of the curve decreases;
3. As the diameter of the nozzle increases, the linear part in the middle of the curve decreases relatively. These conclusions show that increasing the magnification of the gas meter can increase the magnification of the air momentum meter, but also reduce the initial measurement gap and increase the gas consumption of the gas source.

By combining the above two points, we can conclude that when the diameter of the measuring nozzle is equal to the diameter of the main nozzle, the optimum value of amplification and linear range can be obtained.

7. Summary

(1) Through theoretical research, the expressions of the back pressure and clearance function and the change rate of the middle and high pressure back pressure pneumatic measuring system under four working conditions are obtained when the nozzle baffle is curved surface. It provides a powerful theoretical basis for the research of dynamic honing, pneumatic measurement and measurement accuracy under experimental conditions.

(2) The relationship between the diameter of the curved baffle plate and the accuracy of the measuring system is studied. Back pressure chamber pressure $p_x$ is not only related to measuring system working pressure $p_c$, main nozzle inner diameter $d$, measuring nozzle inner diameter $d_1$ and measuring gap $S$, but also related to the diameter of surface baffle $D$. And the larger the diameter of the curved baffle is, the smaller the pressure $D$ of the back pressure air chamber is $p_x$. The larger the magnification of the pneumatic shift is. The slope of the line

(3) The influence of the characteristic equation of the curved baffle and the characteristic equation of the baffle plate on the measurement accuracy is analyzed and compared. It is shown that the measurement accuracy of the characteristic equation of the curved baffle is higher than that of the planar baffle, and the accuracy is $\frac{d^2}{8D}$. When the honing accuracy is $m_1 m$ and $D < 125d^2$, the influence of
the diameter of the curved baffle on the measurement accuracy must be considered. The characteristic equation of the baffle cannot be used to study the characteristic equation of the curved baffle.

(4) The air path structure and nozzle parameters of the curved nozzle flapper mechanism in the honing pneumatic measuring system are optimized. Under the condition that the baffle is curved surface, the pressure clearance curve of different main and measuring nozzles is obtained by adjusting the model parameters, and then the law is found according to the result, and the design parameters are optimized.

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