We have developed a high-precision air bearing spindle capable of reducing spindle run-out in the axial direction to a few nanometers. Regarding radial bearings, changing the conventional structure has improved stiffness, and regarding axial bearings, an actuator was added to dampen axial-direction vibrations and decrease axial run-out. A spindle incorporating these radial and axial bearings was designed, and characteristics were confirmed by numerical analysis. Furthermore, a prototype was manufactured, and performance was validated through experiments. Performance was shown to be superior to that of the conventional spindle.

**Key Words:** air bearing spindle, axial run-out, actuator, control, bearing stiffness, machine tool

1. **Introduction**

The demand for higher level machine tools is increasing year by year. Accompanying this, further high precision is demanded of spindles and spindle supporting bearings that are elements of machine tools. JTEKT, as a manufacturer of both machine tools and bearings, has developed machine tools and bearings that can meet these customer demands based on our technology concerning various bearings (rolling, hydrodynamic, air and magnetic).

Generally, the air bearing is considered to have the highest precision among various bearing types. Machine tool spindles supported by such air bearings are typically employed for die mold manufacturing involving curved surfaces and micro profiles for the manufacturer of high precision optical components of products like digital cameras and DVD players. In recent years, in conjunction with requirements for higher performance of these products, the level of die mold manufacturing is improving, and the trend is expected to continue in the future. To this end, developments are being made in high precision machine tools and various machining technologies[1, 2].

The reduction of rotational run-out of the air bearing spindle is one of the most important issues to be solved regarding higher precision machining technology. It is because the rotational run-out of the spindle is transferred to the machined surface, resulting in adverse effects on the machining precision. Therefore, up until now, various measures have been taken to reduce spindle rotational run-out[3, 4]. However, these measures have achieved a run-out level of several ten nanometers, which means further reduction of spindle rotational run-out is necessary in order to achieve desired high precision machining.

As such, in order to improve the machining precision, JTEKT has been developing a high precision air bearing spindle capable of reducing spindle rotational run-out.

This paper presents a description as well as the evaluation results of an air bearing spindle with an axial rotational run-out as low as a few nanometers which we have developed for the purpose of installing the air bearing spindle in JTEKT’s product, the CNC high-precision free-form surface machine.

2. **Outlines of Air Bearing Spindle**

**Figure 1** shows a schematic diagram of the air bearing spindle that has been developed. The maximum operating rotational speed of the spindle is 5000 min⁻¹. **Table 1** shows the main specifications of the radial and axial bearings. Both bearings are composed of inherent restriction mechanisms with circumferential grooves. Points of the bearing design are discussed below:

![Fig. 1 Schematic diagram of air bearing spindle](image-url)
2. 1 Structure of Radial Bearing

Conventionally, two radial bearings have been located closely adjacent to each other between the two opposing faces of the axial bearings. In this development, the two radial bearings are located apart from each other, as shown in Fig. 1, on either side of the axial bearings with a diameter twice doubled. In other words, this structure is intended to minimize tilting of the spindle when loaded with heavy workpieces or jigs, while improving bearing stiffness. Figure 2 shows the results of a dynamic characteristics analysis on radial bearing stiffness. The developed spindle has a higher resonance frequency than that of the conventional spindle, as well as improved stiffness approx. five times higher up to the 200 Hz range. From the above, it is obvious that the changes made to the developed bearing structure make the spindle strong against external disturbance during machining.

![Fig. 2 Dynamic characteristic of radial stiffness](image)

2. 2 Structure of Axial Bearing and Study of Rotational Run-out Reduction

The developed axial bearings support the spindle with two axially opposing bearing faces, where an actuator composed of an air pad and a piezoelectric element (hereinafter referred to as PZT) is located behind the motor. Moreover, the air pad has an inherent restriction mechanism with circumferential grooves and functions as a compact air bearing. By using this actuator, minute displacement of the spindle can be controlled to reduce axial rotational run-out. The function and effects of this actuator are described below:

The means of reducing spindle axial run-out must have the following two capabilities:

1. Provide external force to the rotating spindle in a non-contact form
2. Control displacement at a nanometer-level

Table 2 shows means of accomplishing the above ① and various characteristics comparison. In either case, it is difficult to accomplish the above ② because of issues in resolution. Therefore, in order to solve the issue of not obtaining resolution, a high resolution control mechanism has been developed. A schematic diagram of this mechanism is shown in Fig. 3, and its rationale is explained below:

In order to control the minute displacement of the spindle, clearance between the spindle and the air pad is changed by moving the air pad with the PZT, thereby changing the force applied on the spindle. In order to formulate the characteristics, axial bearing and air pad characteristics are assumed to be in accordance with a general vibration model. Supposing a spindle mass of M, a damping coefficient of C, a spring constant of K for the axial bearing, a damping coefficient of \( C_m \) and a spring constant of \( K_m \) for the air pad, the relationship between the displacement of the air pad \( X_a \) and that of the spindle \( X_s \) can be expressed as follows by solving the equation of motion:

\[
X_s = \frac{C_m s^2 + K_m}{(C + C_m)s + (K + K_m)} X_a \tag{1}
\]

From equation (1), if dynamic terms are not considered, the equation can be simplified as follows:

\[
X_s = \frac{K_m}{K + K_m} X_a \tag{2}
\]

In equation (2), if \( K:K_m \) is considered as \( 99:1 \), \( X_s \) will then equal 100:1 and a movement of the air pad by 100 nm will result in spindle displacement of 1 nm. In other words, it is possible to control spindle displacement at a more minute level than PZT resolution which changes clearance and to achieve displacement control at a nanometer level. Table 3 shows the main specifications of the actuator. The PZT used is a product of Piezomechanik (Model: HPS 150/20-15/12).

The effect of activating the actuator was determined by an analysis. These results are shown in Fig. 4. Here, for convenience, the result is shown non-dimensionally based on amplitude without control. A PI control method is used with the control parameters obtained via the ultimate sensitivity method. Although the effect varies depending on the driving frequency, an amplitude ratio below 1

![Fig. 4](image)
was observed at approx. 450 Hz or less. This indicates that control could help reduce rotational run-out. As for the developed spindle, which has a maximum rotational speed of 5 000 min⁻¹ (83.3 Hz), it is evident that control can reduce the rotational run-out to at least one-third or less throughout the operating speed range.

### Table 2 External force generation method and various characteristics

<table>
<thead>
<tr>
<th>External force generation method</th>
<th>Response</th>
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<td>Magnetic force</td>
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3. Basic Performance Evaluation of Air Bearing Spindle

#### 3.1 Bearing Stiffness

As the basic performance of the spindle, the bearing stiffness was measured. Bearing stiffness was determined by the gradient of a straight line obtained from the relationship between the load on the spindle and its displacement. The radial stiffness obtained was 147.5 N/μm, or approx. 4.3 times as great as that of the conventional spindle (34 N/μm). Also, the dynamic characteristics were found to be almost equal to the analysis result. This indicates that the change in the bearing structure had a positive effect. With regard to the axial stiffness represented on the load-displacement diagram, as shown in Fig. 5, the developed spindle was free of any axial displacement under a load up to approx. 11 N due to the effect of the control, making it evident that infinite stiffness was achieved. When the axial load exceeded this threshold, displacement occurred even greater than that of the conventional spindle due to the force from the air pad becoming saturated (PZT stroke limit) with the stiffness being lower than that of the conventional spindle. The reason for this is that the axial bearing stiffness was designed to be capable of both providing a sufficient range of spindle displacement control and resolution. Since high-precision machining generally incorporates very small cutting depth and feed rate, the machining load acting on the spindle is low in the range of 1 N. From the above, as the spindle displacement generated by machining loads on high-precision machining operations can be adequately compensated by this control system, it can be said that the developed spindle has high stiffness.
3. 2 Rotational Accuracy
3. 2. 1 Rotational Accuracy Evaluation Method

For the purpose of evaluating spindle rotational accuracy, the following methods were used for both the radial and axial rotational accuracies, as shown in Fig. 6:

(1) To measure radial rotational accuracy, a master sphere was used (deviation from spherical form: 0.05 μm) as the target, on which displacement sensors were attached in horizontal and perpendicular directions. The Lissajous waveforms were obtained at a spindle rotational speed of 60 min⁻¹, and the difference in radii of the maximum and minimum circles was determined as the rotational accuracy.

(2) To measure axial rotational accuracy, a measurement target spherically machined on the end faces in our CNC high-precision free-form surface machine AHN®10 was used. The axial rotational run-out was determined as the amplitude of the axial run-out measured by a displacement sensor attached on the center of the rotating spindle. The measurement was carried out at three different rotational speeds, 600, 3 000 and 5 000 min⁻¹, each representing grinding, cutting, and the machine’s upper limit.

Figure 7 shows the measurement result of the radial running accuracy. The measurement values include shape accuracy of the master sphere on which the sensor was applied. Compared to the conventional spindle with a rotational accuracy of 0.089 μm, the developed spindle had 0.061 μm, revealing it was equivalent or better.

Figure 8 shows the measurement result of the axial running accuracy at, for example, a rotational speed of 600 min⁻¹. It was revealed that while the axial rotational run-out of the spindle without control was practically equal to that of the conventional spindle at 0.0324 μm, the rotational run-out was reduced to 0.0031 μm when control was added. In other words, it was established that by applying this control, a rotational run-out could be reduced to approximately one-tenth in grinding operations. Figure 9 shows a comparison of analysis measurement and actual measurement results of the axial rotational amplitude ratio both with and without control. At a driving frequency of 10 Hz (rotational speed of 600 min⁻¹), the actual measurement and analysis measurement results are practically consistent. But with the frequency or rotational speed increasing, the actual measurement result gradually shows less effect than that of the analysis. As conceivable factors contributing to such deviation from analysis, the influence of high-frequency components synchronized with rotational speed, noise, etc., can be raised.

![Fig. 6 Rotational accuracy evaluation method](image)

![Fig. 7 Radial rotational accuracy](image)

![Fig. 8 Axial run-out at 600 min⁻¹](image)
4. Conclusions

In an attempt to further improve machining accuracy of high precision component dies, we have developed a high precision air bearing spindle capable of reducing the rotational run-out, with the results as follow:

1) The radial stiffness has been increased by approx. 4.3 times due to changes in the radial bearing design.
2) Regarding axial stiffness, incorporation of control by actuator on the axial bearing has achieved infinite stiffness under loads up to approx. 11 N.
3) The radial rotational accuracy was 0.061 μm, which was equal or above the conventional spindle.
4) Regarding axial rotational accuracy, an experiment at a rotational speed of 600 min⁻¹ in the presumed grinding operation speed range, resulted in 0.0031 μm, a rotational run-out of a reduction of one-tenth in the case of no control.

References