23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

DESIGN, DEVELOPMENT AND ERROR ANALYSIS OF AN AEROSTATIC ROTARY TABLE

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Abstract. *Rotary tables are equipments in precision machinery applied in five-axis Machine Tools and Coordinate Measuring Machines (CMM), offering rotational (C-axis) and tilting motion (A-axis), allowing to obtain several configurations for manufacturing or inspection of parts with complex geometries. Every day is increasing demand for high accuracy, high efficiency and smaller errors in the positioning of the tool (or part) in precision machines, thus ensuring their high confidence, and the use of aerostatic bearings offer to the equipment constructive innovations. In this context, this work presents the mechanical design, the development and error analysis of a prototype of an aerostatic rotary table. This study had emphasis at the analysis of a prototype that uses the air as a working principle for reducing friction between moving parts, increasing the mechanical efficiency, and its influence of motion error is also discussed based on the experimental results. For the geometrical errors analysis, tests were realized in laboratory using a Double Ballbar (DBB). All the tests are performed with only one axis moving, observing the behavior of the system for different angles of ‘C’ and ‘A’-axis.*

Keywords: *Precision machines, Rotary tables, Aerostatic bearings, Coordinate Measuring Machines.*

1. INTRODUCTION

The need for components with high dimensional accuracy and surface quality has encouraged many researchers around the world to focus on the development of measurement of machine tools and instruments to achieve the desired levels of accuracy (Porto, 2004). The increasing need for manufacturing and measuring parts of complex geometries with high accuracy, five-axis machines are used in various applications requiring high accuracy (Ibaraki *et al*, 2012).

Machines with multiple axes are usually composed of three axes performing linear motions and two rotational movements, these known as rotary tables. The rotary tables incorporate high precision and good stiffness in machine tools and Coordinate Measuring Machines (CMM). In general, one of the axes is used to rotate (*C*-axis) and the other to tilt (*A*-axis) the piece to be machined or measured by significantly increasing tool access probe or sensor to provide a significant gain time material removal or inspection by the sensor.

With the assistance of these rotary tables, provided to the manufacture industry several advantages, such as the significant reduction of set-up time of a machine, better accessibility tool and more flexibility during the machining operations (WANG *et al*, 2013).

The constructive forms of a machine tool or measuring machine are related with the measurement volume, measurement uncertainties, the technology used by manufacturers and others. Constructive factors, such as aerostatic bearings to replace the recirculating ball guides, allowing manufacturers to decrease the machine level of uncertainty (Nóbrega, 2011).

The use of aerostatic bearings in engineering design, provided a significant increase in mechanical efficiency due to reduced friction between components that perform movement, and became prominent elements in search of greater accuracy, stability and high performance to high rotations (Balestrero & Purquerio, 1999). All this thanks to a thin film at high air pressure can bear the load between the moving surfaces, that is, the film thickness characterized the bearing stiffness (Freitas & Prata, 1995).

The rotary tables, besides the advantages presented, also have disadvantages, such as for errors that arise during assembly and operation of the machine. The prerequisite for the proper design of a machine is the measurement and identification of the origin of errors, which depend on the measuring instrument and the error identification techniques. The accuracy of the results obtained by a rotary table is linked to several factors, quote: the mechanical precision of the machine frame; the drive system of the machine; the data acquisition system; the accuracy of the machine control system; the machining strategy or measurement of the piece; the fixing of the piece and its mechanical properties (Wang *et al*, 2013).

Based on the above, this work presents the mechanical design, the development and error analysis of a prototype of an aerostatic rotary table. This study had emphasis at the analysis of a prototype that uses the air as a working principle for reducing friction between moving parts, increasing the mechanical efficiency, and its influence of motion error is also discussed based on the experimental results.

2. ROTARY TABLES: OVERVIEW

Many studies include the use of ballbar as a measuring instrument for identify geometrical errors on rotary tables. Khan and Chen (2010) created a methodology that was developed and implemented for the characterization, evaluation and quantification of errors in rotary joints of five-axis machine tools using the Ballbar system.

Zhu *et al* (2012) presents an integrated method for modeling, identification and compensation of geometric errors in machine tools, and the ballbar was used to identify six errors due rotary tables.

Lee and Yang (2013) evaluating the accuracy of a machine tool through a spherical deviation model based on measurements using the ballbar in the measurement planes XY, YZ and ZX, and (2013-b) also presented a study of position independent geometric error (PIGE), including offset errors and squareness on rotary axes of five-axis machine tools, using the Ballbar in measurements and checking through numerical compensation.

Lei *et al* (2007) present a new method that uses the double ballbar to inspect motion errors of the rotary axes of five-axis CNC machines tools. It was observed that when CNC machine tools are used for high feedrate contourning, whereby two or more axes are driven simultaneously, significant feedrate-dependent motion errors appear.

Tsutsumi (2013) describes a calibration methodology in five-axis machines, with two rotary axes, using the ballbar, and proposed a method of correction of deviations to achieve higher accuracy. Zhang *et al* (2013) proposed a method of geometric error detection measurement, using the ballbar and an approach developed to give assistance in the measurements on rotary tables of five-axis machine tools. Chen *et al* (2014) shows in his research an identification model of geometric errors based on the homogeneous matrix, using measurements with the Ballbar system in a machining center with four-axis, in order to decrease the influence of the inaccuracy of the measured parameters.

3. PROJECT AND DEVELOPMENT OF AN AEROSTATIC ROTARY TABLE

For this work, an aerostatic rotary table was developed, where the two rotate axis was based in an usual configuration in five axis machines, i.e., the *C*-axis realize the rotate motion and is perpendicular to *A*-axis, that realize the tilt motion. This configuration allows that the device movements the workpiece at different angles during the measurement.

The Figure 1 presents the project design developed, using the NX software, by Siemens®.

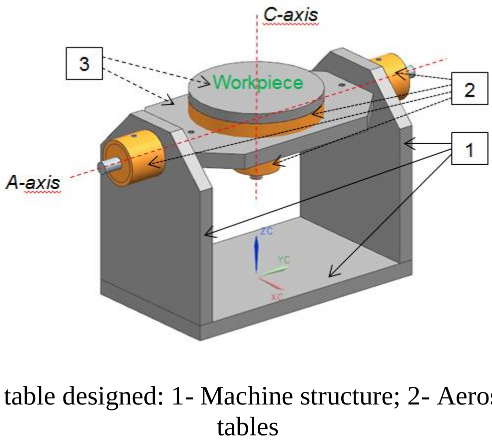

Figure 1. General view of the rotary table designed: 1- Machine structure; 2- Aerostatic bearings; and 3- Rotate and tilt tables

The rotary table is composed for three parts:

Part 1: Is the machine structure. There, all other components of the system are mounted. The whole structure was designed using aluminum, besides being a material having the required strength, also has low specific weight;

Part 2: Are the aerostatic bearings. The bearings were designed to support the loads applied. The material chosen was the brass, metallic alloy consisting of copper and zinc, in the manufacture of parts. Four bearings were developed, being three radial bearings and one axial;

Part 3: The tables that compose each rotary table axis are shown. One of them is the tilt (*A*-axis) and the other one is the rotate (*C*-axis). In coordinate measuring machine the workpiece to be measured will be fixed on the last one. The material used was aluminum, for the same reason it was chosen for the structure.

The Figure 2 below presents an exploded view of the prototype, where can see the assembly details of the components.

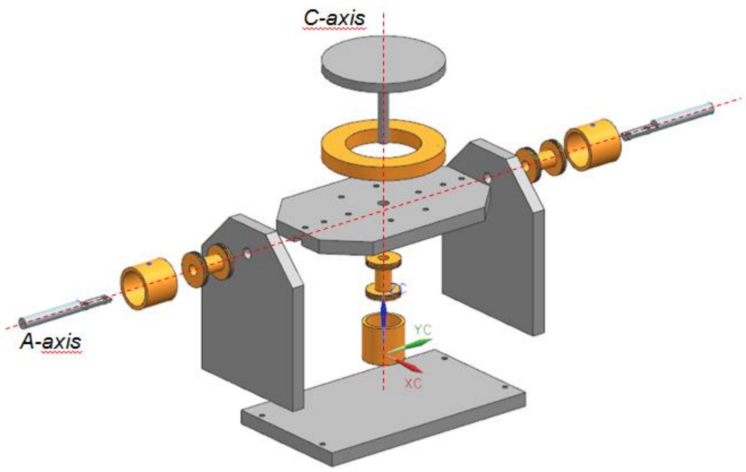

Figure 2. Exploded view of the rotary table developed

The aerostatic bearing installed has the function to separate two surfaces through by a thin layer by fluid, in this case the air that is compressed by a determinate value. The air inlet in a hole, and the flow's outlet occurs in various feed holes with small diameter, uniformly distributed in the bearing, as shown Fig. 3, creating a lubricating fluid layer separating the fixing part which comes into the movement, decreasing the friction in the regions of the parts are in motion.

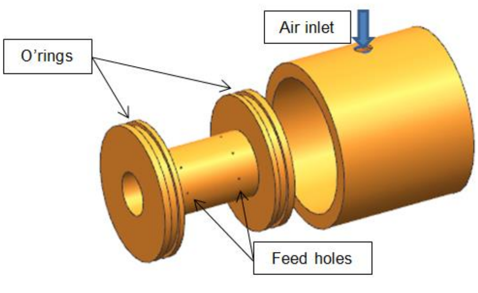

Figure 3. Aerostatic bearing designed

The air consumption values and machine stiffness can be estimated. According the model presented by Venkatesh and Izman (2007), the geometry of each bearing set type was used as the value for the feed pressure 4.0 bar = 406.8 kPa, and considering other parameters default values, such as clearance between the shaft and bore 0.0127 mm; working temperature of 15° C and pressure ratio of 0.4. For these conditions, the radial bearing have a flow demand 0.841 l/min and rated stiffness on the order of 4.60 kN/mm. For the thrust bearing, the flow demand is around 15.65 l/min, with estimated stiffness in 131.07 kN/mm, after applied the appropriate corrections.

It can be concluded that the above estimate values for the air circuit attend sufficiently the operation demand. With respect to stiffness, the estimated values also attend the design requirements, ensuring the operation of the system to the experimental tests.

The parts that compose the rotary table were made by conventional machining methods, such as: milling, lathe, drilling, adjustment and polishing surfaces by sanding. Figure 4 shows the mounting system, where you can observe the connections to the air system in each bearing.

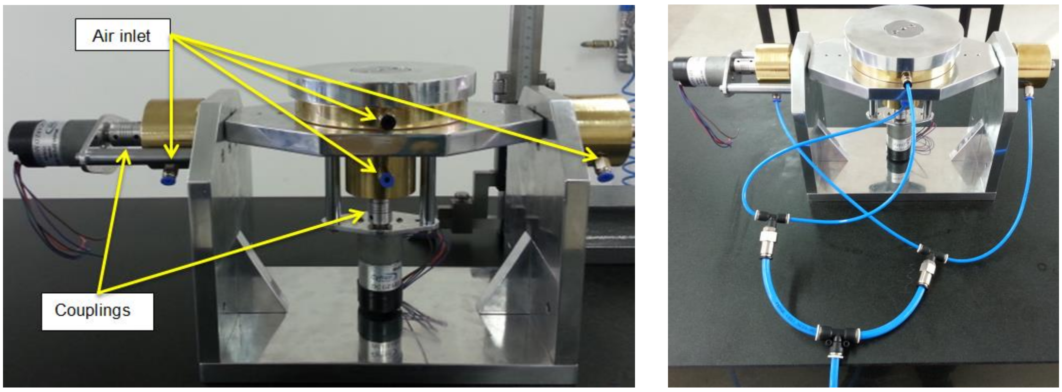

Figure 4. Aerostatic rotary table developed

Flexible couplings for motion transmission were mounted between the servo and the tables. The choice of this type of coupling ensures misalignment compensation because any small movements originated during the air supply in the bearings.

The air that will serve to feed the aerostatics bearings is captured from the external environment, through various processes which include a compression system, which is responsible for a compressor that raising the pressure of the air; a storage system, comprising to the reservoir connected to the compressor; a system of treatment that consists of passing the air through filters for removal the impurities and through a dryer, where it will be reduced to the maximum the humidity present in the air by a cooling system; ending by a pressure control valve and flow out with these parameters and controlled by a specific pipe according to reach the bearings.

After the development of the structural part of the rotary table, an instrumentation required for the movement of the axes has been developed for carrying out the experimental tests. Schematically, Fig. 5 shows all the components of this instrumentation, indicated by block diagram for data acquisition and drivers.

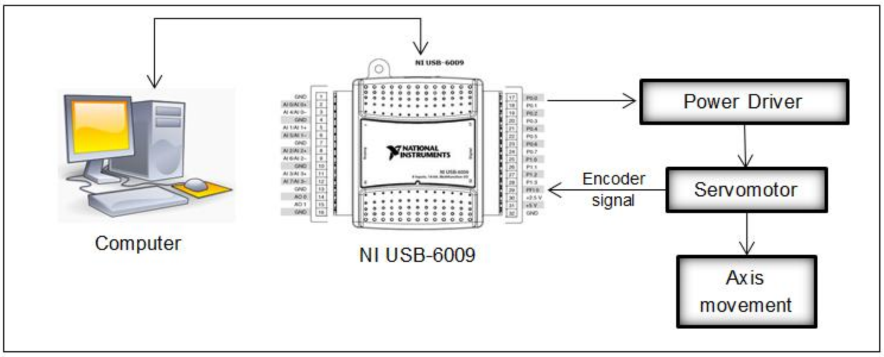

Figure 5. Instrumentation realized for the rotary table

These components form a control system in open loop where the displacement performed by the table is determined by the number of pulses sent by the encoder that is coupled to the servomotor without the feedback loop.

For driving the servomotor, a data acquisition board from National Instruments® USB-6009 model was used. This board enables communication via USB port to a computer, through Labview® Software.

4. EXPERIMENTAL TESTS AND RESULTS

For realize the experimental tests, was used a Double Ballbar (DBB) system, model QC20-W by Renishaw®. This equipment measures existing geometric errors through circular movements or arcs executed by the machine. Small deviations in the radius of this movement are measured by the transducer and sent through by software, where the results are displayed on the screen.

The DBB has the following specifications: maximum sample rate 1000 samples/sec; nominal length of the transducer 100 mm (between the centers of the spheres); measuring range of -1.0 a +1.0 mm; resolution 0.1 µm and accuracy of ±0.5 µm (20ºC).

If the machine had no errors, the graph would show perfect circle, and the radius is equal to the length of the measurement bar (transducer). The presence of any errors will distort this circle, by the addition of peaks along the circumference and possibly making it elliptical. These deviations reveal problems and inaccuracies in the numerical control, servo control system and the machine axes (RENISHAW, 2014). The errors measured by the DBB are overall motion errors, including position-dependent motion errors and tracking-speed-dependent motion errors (Lei *et al*, 2007).

To install the ball bar in the machine, an adaptation was performed by installing a flat bar of dimensions: 50 mm wide and 190 mm long in the upper surface of the rotary table (*C*-axis), where was installed the moved part of the DBB. This adaptation ensures a length of 100 mm, required distance between the centers of the measuring instrument precision ball. In parallel, was developed an aluminum structure, fixed on the tilt table (*A*-axis), where were installed the others components, the fixed parts of the DBB system, as shown the Fig. 6.

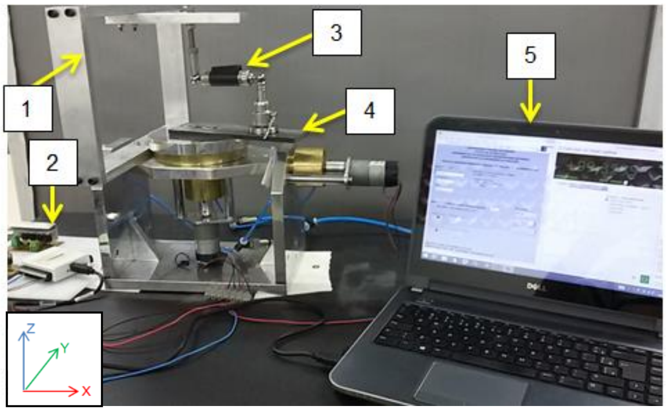

Figure 6. Experimental tests in the system: 1- Aluminum structure; 2- Control system components; 3- DBB transducer; 4- Flat bar; 5- Computer

This structure allows that the measuring system can be in the same position for different angles of the tilt table, reducing errors during the tests. During the tests, between the fixed part and the moved part is installed the DBB transducer, responsible to capture the movement signals. The measuring ball which is mounted on the structure remains stationary while that the measuring ball mounted on the table moves along a circular path formed in accordance with the tilt and rotational axis of movement settings. The captured data is synchronized with the circular motion by trigger signals, and these signals are sent to the computer via bluetooth.

Settings were implemented in the equipment in the following manner: the tilt axis was positioned in the horizontal position (0°), adjusted with a level meter. Then, the rotational axis is moved 720° in the counter-clockwise (CCW) direction followed of a movement of 720° clockwise (CW) direction. The DBB moves in CCW or CW in data capture arches of 360° with 180° of overshoot arc, where this one is the arc traveled by the Ballbar transducer before and after data capture arc.

The Renishaw analysis software analyzes the captured data and evaluates the circular hysteresis, and circular deviation of circular paths that are produced by the machine movements. The Ballbar test on an aerostatic rotary table is shown in Fig. 7. The result was obtained for a feedrate of 5900.0 mm/min, approximately.

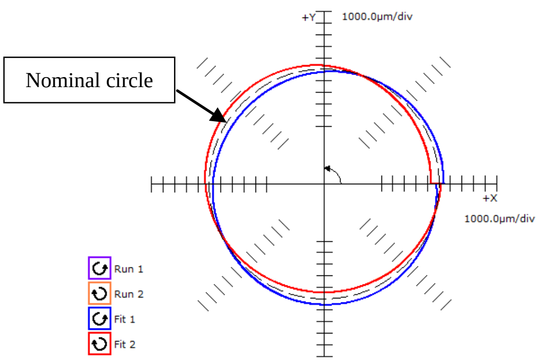

Figure 7. DBB results display

The blue curve is the adjusted data in CCW direction, and this curve is overlapped the purple curve, that is the captured data. At same form, the red curve is the adjusted data in CW direction, overlapped the orange curve. And the black dashed curve represents the nominadl circle, defined by Ballbar model, with radius 100 mm. The experimental test has relatively large geometric errors, as can be seen the measured data.

The Table 1 shows the result analysis, generate through by DBB software, quantifying the magnitude of the geometric errors caused by dependent-position motion errors.

Table 1. Geometric errors results

Error	Magnitude	
Backlash		
X	+ 746 µm (→)	- 38.6 µm (←)
Y	+ 1.8 µm (↑)	- 13.1 µm (↓)
Reversal Spikes		
X	- 9.6 µm (→)	+ 6.6 µm (←)
Y	- 0.9 µm (↑)	+ 2.4 µm (↓)
Lateral play		
X	- 698.1 µm (→)	- 84.7 µm (←)
Y	- 98.7 µm (↑)	+ 30.8 µm (↓)
Cyclic error		
X	8.0 µm (↑)	13.2 µm (↓)
Y	2.9 µm (↑)	24.8 µm (↓)
Straightness		
X	- 15.6 µm	
Y	9.6 µm	
Servo mismatch		
0.92 ms		
Squareness		
0.05399°		
Scaling mismatch		
- 105.6 µm		
Circularity		
1248.4 µm		

The arrows (→ / ←) at the table are used to indicate the direction of the *X*-axis in the graph, if it is positive (+*X*) or negative (-*X*), respectively, and the arrows (↑ / ↓) are used to indicate the direction of the *Y*-axis, i.e., the first is used to indicate (+*Y*) and the other the direction (-*Y*).

About the table, we can highlight that presents a large Backlash on direction *X*-axis. It can be caused due to the clearance in the machine drive system, mainly in the air bearings, causing movement error when the drive direction is reversed. These experimental results allow observing the behavior of the developed prototype, by identifying the points that shall be improved in the system. Therefore, further experimental work should be developed in order to improve the prototype performance.

The prototype also presents a high slop in the *X* direction. The lateral play is a lateral displacement between the data captured of the clockwise and counter-clockwise. In the machine, its represents the clearance on the air bearings, causing the machine axes to move perpendicularly to their guides during reversal of the direction of the axis. This effect is opposed to the degree of backlash. The backlash is a radial error, while the lateral play is a tangential error.

The Squareness error is very present in the prototype. Is the oval or oblong shape on the graph, distorted along the diagonal 45° and 135°, in both direction. Positive squareness error indicates that the angle between the *X* and *Y*-axis exceed 90°. Squareness error indicates that there is a misalignment in the machine, due a clearance in the bearings.

And other parameter of high influence in the results was the circularity, at about 1248.4 µm. The value represents the difference between the lowest and the highest radius registered by the Ballbar during the data capturing arches movement. The circular deviation was determined by DBB, and the values were 794.4 µm for CCW direction, and 929.7 µm for CW direction.

5. CONCLUSIONS

The application of the DBB method to inspect the motion errors of an aerostatic rotary table has been investigated. The measuring method was applied in a prototype of rotary table, that use air bearings to reduce the friction between the moving parts. This methodology allows the geometric error identification of rotary tables in practical and fast way compare to the other methods such as interferometer laser and auto-collimator.

However, further experimental work will be developed in order to improve the design of the developed table, aiming to reduce the clearance in the air bearings. In addition, other experimental tests with different *A*-axis angles and different feedrate will be developed.

The error measurement methodology of rotary tables using the ballbar system, presented in this paper, proved to be an important tool for measuring their geometric errors such as: backslash, reversal spikes, lateral play, cyclic error, straightness, servo mismatch, squareness, scaling mismatch and circularity. Additionally, it contributes to minimize these errors still in early design stage and thus obtain an improvement in the rotary table accuracy, in particular those applied in Coordinate Measuring Machines.

6. ACKNOWLEDGEMENTS

The authors would like to thank Universidade Federal da Paraíba (UFPB), Programa de Pós-Graduação em Engenharia Mecânica (PPGEM) and Instituto Federal de Educação, Ciência e Tecnologia da Paraíba (IFPB) for financial and scientific support for this research.

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