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A STUDY ON THE OPTIMAL DESIGN OF AIR POCKETS IN AN AIR BEARING APPLIED TILTING INDEX TABLE

The tilting index table has attached to CNC machining center with 3axes, it can be improvement of its performance and its machining efficiency. The tilting index table is a key unit in order to manufacture some non-rotational and 3-dimensional parts, using the conventional machining center. The tilting index table is directly connected to a processing object. Regarding the increase in the deflection of the table, it directly affects processing objects and increases errors and that makes impossible to obtain desired processing precision. Thus, this study performed the shape optimization of air pockets in order to minimize the deflection presented in the existing table. In the numerical optimizing method for implementing optimal design, the general full factorial design and response surface method in the design of experiments were used. A finite element analysis was used for computational experiments in which the finite element analysis was performed by using the ANSYS Workbench, which is a type of commercial FEM tool. In addition, the analysis of the results was performed by using the commercial program, Minitab 15. The results show that the optimum design results is better than those of the initial design.

1. INTRODUCTION

It is very important to implement the high value added production that achieves a high efficiency production system and increases price competitiveness in order to flexibly adapt rapid changes in markets in various recent industrial fields. Thus, various developments in the field of machine tools, such as high speed, high precision, multi-axis, and composition technologies, have been conducted for improving processing efficiency. A tilting index table that is installed at a machine tool and combines rotational and tilted axes can be regarded as an example of the multi-axis technology. For processing the existing products with complex three dimensional shapes, a four or five axes machine tool is required, but such a machine tool represents no competitiveness in markets due to its high cost. However, it is possible to achieve the product processing with high precision as low cost by installing a tilting index table [1]. The tilting index table is a device that is directly connected to a processing object.

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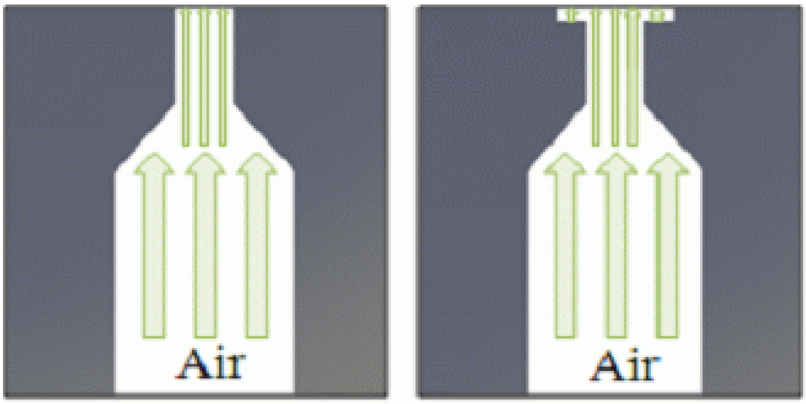
Because it is not possible to obtain desired precision as the deflection of the table is increased, the strength of the table should be regarded through considering such deflection. Thus, there is an upward tendency that applies air bearings for the tilting index table increasingly. Because the air bearing represents no friction and wear and has high strength and damping and that can implement the high strength, high speed, and low noise operation of the tilting index table [2].

A change in restrictor factors can be applied as a method that obtains high strength in the air bearing applied to the tilting index table. The representative restrictor factors used in air bearings are self-restrictor, surface-restrictor, and porous-restrictor. Fig. 1 illustrates the self-restrictor and surface-restrictor, respectively [3].



(a) Self restrictor (b) Surface restrictor

Fig. 1. Restrictor pattern

In this study, we performed a structural analysis of the tilting index table that applies surface-restrictor based air bearings. Also, this study achieved the shape optimization of the air pockets used in the air bearing by varying the size and location of its air supplier. We investigate the structural validity of the optimized shape through a structural analysis under the same constraint and load conditions.

2. TILTING INDEX TABLE WITH AIR BEARING

2.1. BASIC DESIGN OF A TILTING INDEX TABLE

The development specification of the tilting index table using air bearings were determined by the load capacity of 200kgf, A-axis maximum rotation angle of 150 ˚ (+30 ˚ to -120 ˚), and C-axis maximum rotation angle of 360 ˚ , in which the maximum rotation capacities of the A and C axes were determined by 100 and 250 rpm, respectively. Fig. 2 shows the configuration of the air bearing based tilting index table.

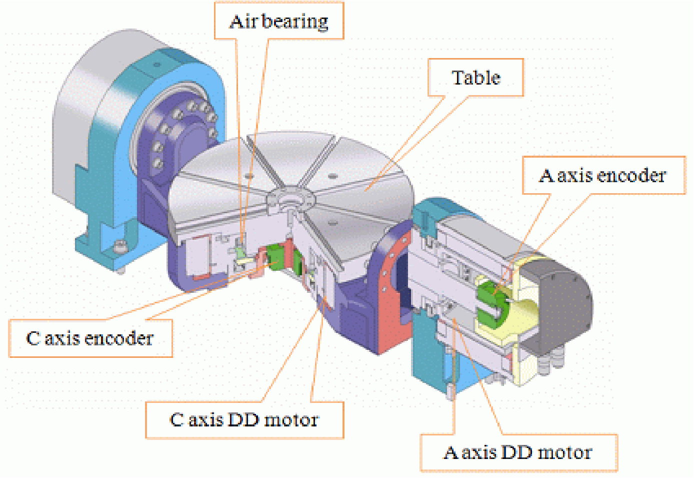


Fig. 2. 3-D model of the tilting index table

Fig. 3 shows the table supported by the air bearing. The air pressure can be transmitted to the table through air pockets. The table is a device that holds processing objects, and the plate makes a rising of the table using the air pressure discharged by the air pockets. The risen clearance, air pressure, and vibration can be varied by the shape, size, and array of the air discharge holes [4].

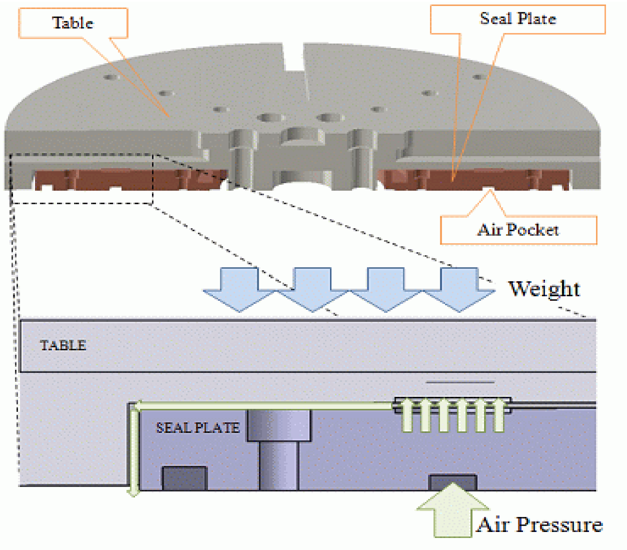


Fig. 3. Air bearing of the tilting index table

2.2. STRUCTURAL ANALYSIS OF THE TABLE

A hex dominant method was applied to perform the structural analysis of the air bearing based table. Half of the table was configured as an analysis model by excluding the symmetric section of the table. Fig. 4 represents a finite element model that has 141,272 nodes and 397,087 elements.

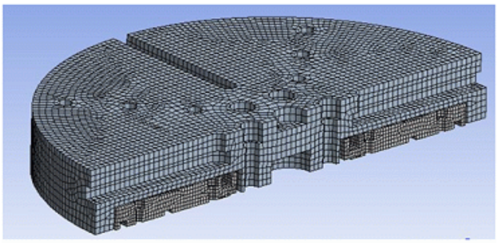
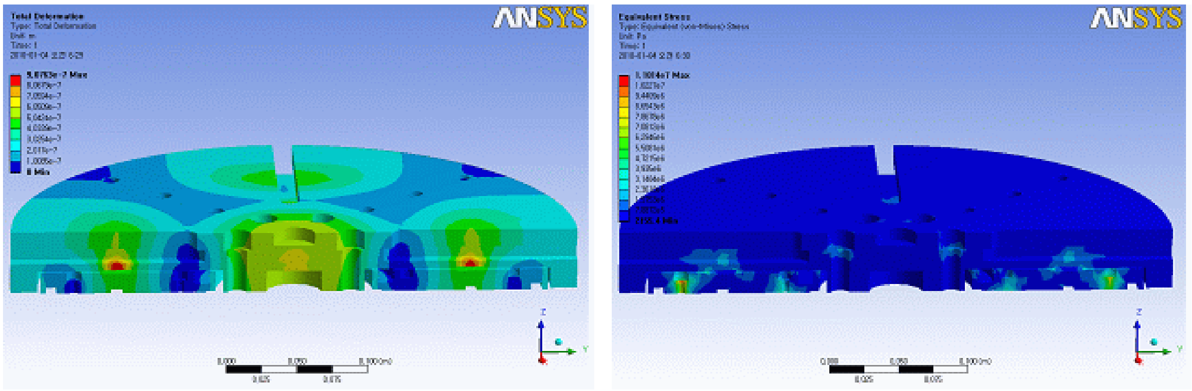


Fig. 4. Finite element model of the table

In boundary conditions, a constraint condition was applied to maintain the conditions that represent no rotations and movements in the bolt joint at the bottom of the plate in which the plate and motor were jointed. In load conditions, the force of gravity was applied to the entire structure through considering the net weight of the table. Also, a load of 2,000N was applied to the joint located at the center of the table where the table and processing object were jointed by considering the maximum pay load. The discharge air pressure was determined by 1MPa. The air pressure was transmitted to the table as a shape of air pocket in which it was assumed that there were no influences caused by air flows besides the pressure transmitted to the air pockets. Tab. 1 shows the material properties of the table that were used in the structural analysis.

Table 1. Material properties of the table

Materials	GC25	SS40
Young’s modulus [GPa]	108	200
Density [kg/m^3]	7,150	7,850
Poisson’s ratio	0.35	0.26



(a) Deformation distribution of the table

(b) Stress distribution of the table

Fig. 5. Result of finite element analysis

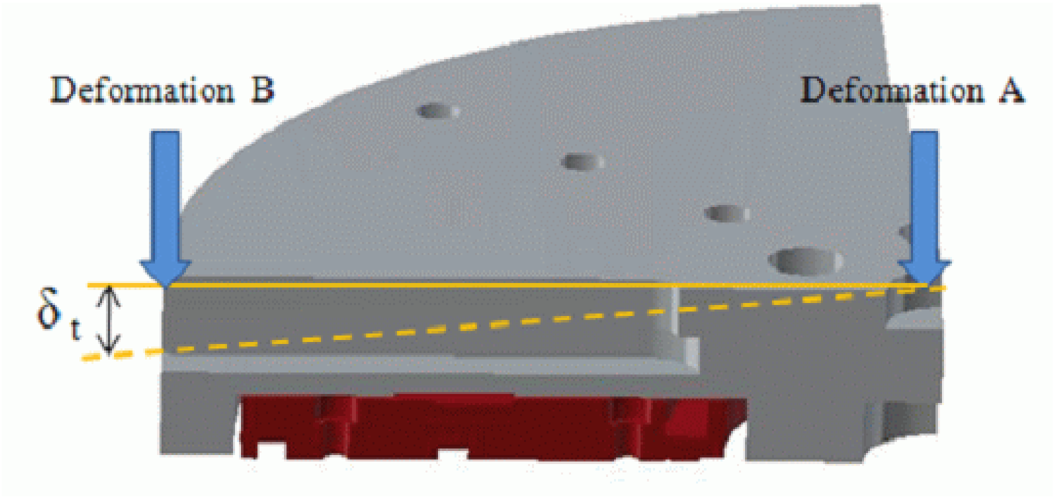


Fig. 6. Deflection of the table

$$\delta_t = |A - B| \quad (1)$$

The structural analysis was performed based on the established finite element model. Fig. 5 represents the maximum deformation and stress of the air bearing based table, respectively. The maximum deformation was 0.907 ㎛ and that was generated at the upper section of the air pockets that was affected by the air pressure. Also, the maximum stress was 11.01Mpa and that was presented at the bolt joint at the bottom of the plate.

Fig. 6 represents the deflection, δ_t, from the center to the skirt of the table in which the deflection was 0.371 ㎛.

3. OPTIMAL DESIGN USING THE DESIGN OF EXPERIMENTS

The table is directly connected to a processing object. Regarding the increase in the deflection of the table, it directly affects processing objects and increases errors and that makes impossible to obtain desired processing precision. Thus, this study performed the shape optimization of air pockets in order to minimize the deflection presented in the existing table. In the numerical optimizing method for implementing optimal design, the general full factorial design and response surface method in the design of experiments were used. A finite element analysis was used for computational experiments in which the finite element analysis was performed by using the ANSYS Workbench, which is a type of commercial finite element method tool. In addition, the analysis of the results was performed by using the commercial program, Minitab 15.

Fig. 7 illustrates the design parameters of the table where X and Y represent the width and length of the air pocket, respectively. Also, R shows the distance between the air pockets and the center of the table.

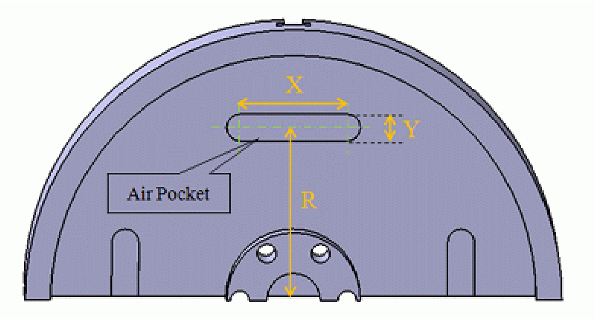


Fig. 7. Design variables of the table

3.1. FACTOR CONFIGURATION EXPERIMENT

For implementing the experiment using the design of experiments, it is necessary to configure major factors in the experiment by analyzing the influence of each factor for their characteristic values. In this experiment, the general full factorial design in a three-level system that has been widely used for configuring factors was used in which the characteristic value was determined as the deflection. Tab. 2 shows the factors and levels used in this experiment.

Table 2. Experimental conditions

Factors	Level		
	Lower bound	Initial value	Upper bound
R [mm]	100	125	150
X [mm]	70	80	90
Y [mm]	10	20	30

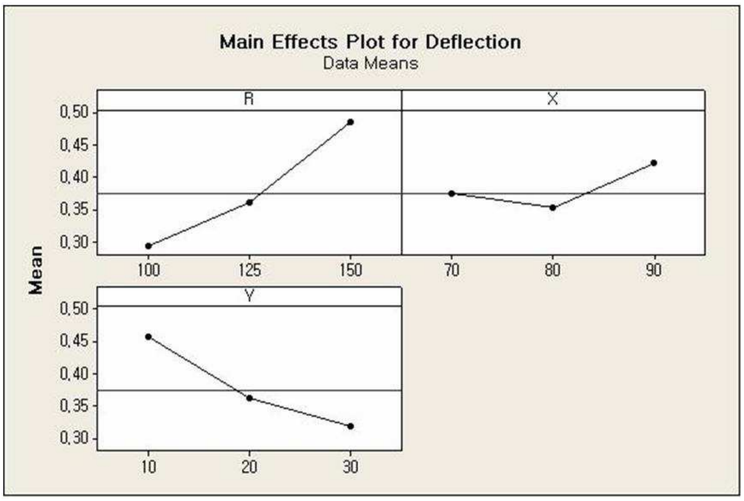


Fig. 8. Main effect plot for deflection

Fig. 8 shows the results of the comparison of the major effect on the deflection where the horizontal line represents the total average, and each individual point shows the average for each level. In the results, the distance between the air pockets and the center point affected the characteristic value significantly. Also, the width of the air pockets affected the characteristic value as a second factor. As a result, in this study, we determined three factors of the air pockets, such as the width, length, and distance from the center point, that affect the deflection.

3.2. RESPONSE SURFACE METHOD

The response surface method is a method in the design of experiments that determines the relationship between one or more response variables and quantitative experimental variables or factor sets. The objective of this method is to determine the condition of factors that optimizes response variables. A central composite design was applied to design the response surface experiment. The central composite design represents cube and axial models, and this study used the cube model that has six axial points, six center points, and eight factorial cube points. The design was performed by the value of α, 1.682, that satisfies the rotationality for these three factors.

Table 3. Results of the computational experiment

Run Order	R [mm]	X [mm]	Y [mm]	Deflection [㎛]	Run Order	R [mm]	X [mm]	Y [mm]	Deflection [㎛]
1	125	80	37	0.077	11	125	63	20	0.412
2	125	80	20	0.371	12	125	80	20	0.371
3	125	80	20	0.370	13	125	97	20	0.333
4	150	90	30	0.686	14	100	90	10	0.512
5	100	70	10	0.530	15	83	80	20	0.065
6	150	70	10	0.382	16	167	80	20	0.591
7	150	90	10	0.298	17	125	80	3	0.561
8	100	70	30	0.079	18	100	90	30	0.278
9	125	80	20	0.371	19	125	80	20	0.371
10	150	70	30	0.473	20	125	80	20	0.370

In the case of the normal probability plot in which points are distributed as a linear manner, it represents a normal distribution. The normal distribution shows a proper result in the experiment. As illustrated in Fig. 9, points are approximated to a specific line.

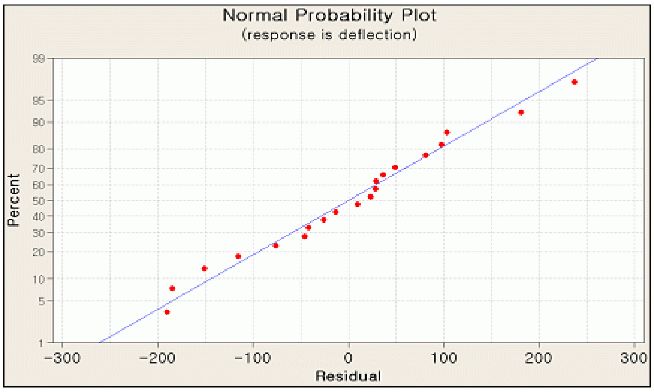


Fig. 9. Normal probability plot of the residuals for deflection

Fig. 10 shows the optimum value of the response variables, which can be obtained from the change in the level of factors, and their level in each individual factor where D represents the satisfaction for the characteristic value. The more approached value of D to 1 shows the more satisfaction for the characteristics aimed by the response variables. Tab. 4 shows the optimum solution of the design conditions, which represent the highest satisfaction, obtained by using the response surface method. It can be seen that the value of R was decreased, and the values X and Y were increased.

Table 4. Results of the optimization

Factors	Initial model	Optimal shape model
R [mm]	125	85.18
X [mm]	80	96.82
Y [mm]	20	31.30

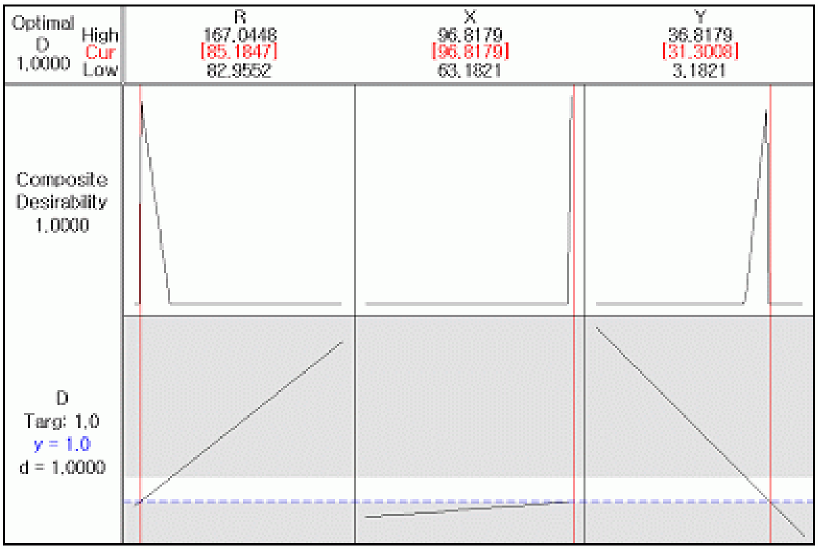
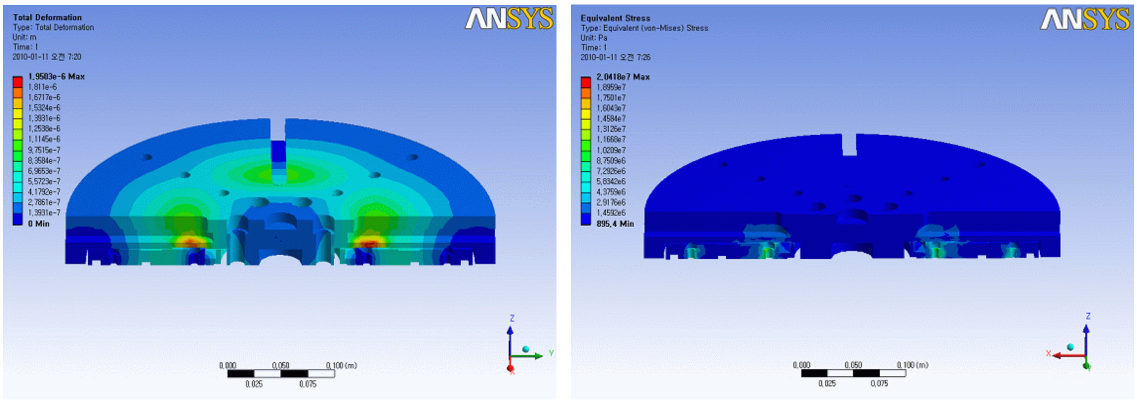


Fig. 10. Optimal deflection condition plot

4. FINITE ELEMENT ANALYSIS BY APPLYING THE OPTIMAL SHAPE

This study performed a structural analysis of the table using the same boundary condition as the existing analysis model. Fig. 11 illustrates the results of the structural analysis of the optimized model. In the results of the analysis performed by applying the optimized air pockets to the table, the deflection was reduced by about 86% from 0.371 ㎛ to 0.052 compared with the existing model. The maximum stress was increased by 9.4MPa from 11.01MPa to 20.41MPa and that was generated at the same position of the existing model. For considering the yield strength of the plate, 230MPa, that was occurred at the position, which represents the maximum stress, it is considered that the model optimized by the safety factor of 11 for the maximum stress is a safe structure.



(a) Deformation distribution of the table (b) Stress distribution of the table

Fig. 11. Result of finite element analysis

5. CONCLUSION

This study performed a structural analysis of the air bearing applied tilting index table and an optimal design of the air pockets using the design of experiments for reducing the deflection of the table. Also, a structural analysis was applied to the optimized model. In the results of the analysis, the conclusion can be summarized as follows.

1) In the results of the structural analysis of the air bearing based tilting index table, it was verified that the structure was safe in which the maximum deflection and stress were determined within the allowable region.

2) In the results of the factor configuration experiment, the influence of each design factor on the objective function was sensitively responded according to the order of R > Y > X.

3) In the results of the estimation of the optimum level combination that minimizes the deflection using the response surface method, it showed that the distance from the center point, width, and length were presented by 85.18mm, 96.81mm, and 31.30mm, respectively.

4) In the results of the structural analysis, which was applied using the optimally designed air pockets to the table, the deflection was decreased by 86%. Also, the safety factor for the maximum stress was 11 and that represents that the structure was safe.

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