Design and Development of Mini CNC Machine for High Performance Machining

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Abstract. : Miniaturized parts and products have widely been required by various industrial manufacturing, e.g., micro molds and dies, electrical and automotive parts, medical devices, etc. However, the mini CNC milling machines are basically unable to perform the parts or products with requiring high precision. The aim of this research is to study the feasibility of developing a mini CNC machine to be able to produce small parts and have relatively high accuracy with the basis of suitable values for investment. Therefore, the upgradation and improvement of the system motion including the X, Y, and Z axes, as well as the machine structure and components of the mini CNC machine in order for enhancing machining performance and accuracy have been purposed. Experimental results of specifically measuring methods and machining tests presented the satisfaction of the upgraded machine's precision and performance.

Keywords: Retrofit, High performance machining, Micro machining, High precision tolerance

1 Introduction

Precision machine tools are increasingly important and needed since miniature parts and products have currently been required. The higher dimensional accuracy and surface quality of these tiny parts are increasingly needed in various industrial manufacturing, e.g., micro molds and dies, electrical and automotive parts, medical devices, etc. However, the prices of ultraprecision/precision machines are still very high while such high-quality mini parts have been desired in higher volume and lower costs. Therefore, the selection of appropriate technology and smart methods to improve quality and productivity with reducing in manufacturing errors and costs are critical issues for manufacturers. Furthermore, CNC/mini CNC machines have widely been used to produce small parts with reasonable precision but are basically unable to perform the parts or products requiring high precision [1]. Thus, the upgradation and retrofit of the system motion of moving axes particular including the X, Y, and Z axes, as well as the machine structure and components of the Mini CNC machine in order for enhancing machining performance and precisions have been purposed in this paper. A conventional mini

CNC machine is adopted to upgrade machining activities with reasonably higher precision for producing miniature parts with maximized dimensional accuracy and quality of machined surfaces. The advantages of using mini CNC machines are that components of the machine comparative small, lightweight, easily transportable as well as cost-effective. However, due to the machine being small and light, there is a trade-off for low stiffness and vibration, especially for the moving parts of the machine tool. Thus, the aluminum-based structure of the machine and linear guideway are considered to retrofit and re-align the machine system for improving balance and movement, leading to machining performances.

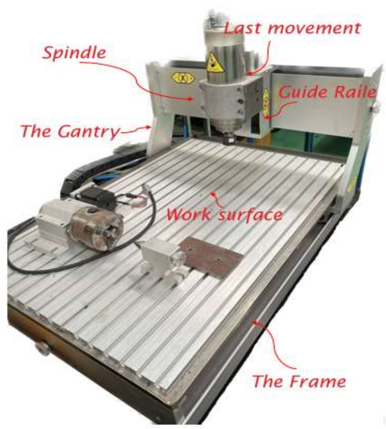

Fig.1 The original state of mini CNC milling machine with size 400 x 600 mm.

The Mini CNC machine set that was used to modify for upgrade has the sizes and details as shown in Table 1. The procedures of upgrade and retrofit activities as well as alignment processes and details will be presented in a separated paper.

Table 1. Specification for this machine before and after upgrade process

Overall Dimension :	**Before**	**After**
Controller	Computer	Computer
X , Y, Z movement	400 x 600 x 100 mm	400 x 600 x 100 mm
X , Y, Z rapid feed	2000, 2000, 1500 mm/min	2000, 2000, 1500 mm/min
Feed System	Ball screw 1605 / Linear guide	Liner Motor
X, Y, Z axis motor	Stepping motor 57BYGH76-3A	-
Input power	220V , 50Hz	220V , 50Hz
Spindle speed	24,000 RPM	24,000 RPM
Spindle motor power	800 Watt	800 Watt
Repeatability accuracy	0.1 mm	0.01 mm
Rack body material	5083 Aluminum folding	7075 Aluminum machine

2 System development and upgradation for mini CNC machine improvement

2.1 Structural material selection for mini CNC machine

Basically, generated heat and thermal effects are always influencing throughout cutting processes. Furthermore, cutting and shearing forces are induced and affected to machine components and workpieces. Thus, the structural machine and machined parts may be subject to thermal deflection and vibration during machining processes. This leads to a decrease in the accuracy of machines as well as difficult to control the size of machined workpieces. Generally, mini CNC machine structure is made of folding steel and connected with welding process which will make the weight of the machine relatively lighter but it will cause the machine to bend and deflect while moving the milling workpiece [2]. In addition, the ball screws are usually installed providing a linearly moving mechanism for the machine and adversely generating high friction and heat while the ball screw drives the machine system. This can cause lots of inertia when the Mini CNC machine moves the axis at a high speed which excessive inertia making not be able to control the positions of workpieces, causing the workpiece to have size and dimension errors. Therefore, the structural material selection and design are performed by re-forming a whole structural machine using high quality aluminum with light and stable properties and replacing the new liner motor drive unit

Fig.2 Ball-Bearing lead screw

2.2 Improvement of motion accuracy on the mini CNC machine

CNC/mini CNC machines are generally not able to produce parts with very high precision because the movements of each axis used the old mechanical drive as so-called the ball screw. This leads to lots of mechanical contacts and errors during machining processes, then friction and thermal effects as well as lacks of accuracies [2]. Thus, accuracy improvement of the moving parts of the mini CNC machine particularly include the X, Y, and Z axes motions are conducted. However, the original control algorithm of motion axes are keep using in the developed machine. Figure 2 shows the relationship between the electrical control and the operating procedure of the mechanical motion axis control unit to control the movement of the axis as accurately as possible

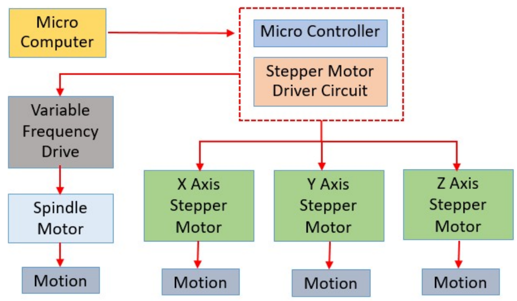

Fig.3 schematic diagram of X, Y, and Z axes motion control units

The original material of the machine structure used in this research was aluminum grade 5083 folding only, which we improved with 7075 aluminum alloy machining grade is 3 pieces with H-shape. The top of the machine is equipped with two liner slides, which are moving along the X and Z axes, respectively. The Z-axis is equipped with a cylindrical spindle head, lightweight and strong attached. The bottom moving axis is a horizontal movement along the Y axis, which is connected to a device called a ball screw. Basically, CNC machines generally use the ball screw to drive the slide axis (linear guideway), which is a straight-line movement. It has a circulating structure by balls with a low coefficient of friction rolling and moving through groves of the ball nut. This groove serves to support the bearing to flow in a straight line throughout this movement as shown in Figure 4.

Fig.4 The structure of the circulating ball bearing

The machine's movements by using ball screws are cheap and well-functioned in varied aspects, however, the downside is limited accuracy due to the friction between the bearing and the groove. Thus, the linear motor with a control unit as the so-called linear drive has been applied instead which has lesser mechanical contacts [3]. Without being connected through mechanical transmissions such as sprockets, chains or belts, and other advantages that liner motors have started to become more widespread in machines that require high precision is able to move quickly, as well as have a high acceleration creating self-braking force. In addition, the resulting speed does not depend on the friction caused by touch no chain or gear required which causes backlash in the system and also does not require lubricant. The working principle is to use a linear guided motor and a cylindrical induction motor that rotates in a rotary motion by changing from a torque-generating motor to drive the machine into a cylindrical unfolding motor horizontally, and when the power is supplied through the stator windings, a magnetic field is generated that runs through the stator surface instead of the magnetic field running in a rotary frame. Alternating or reversing movement is also possible by alternating phases connected to the coil [4]. Thus, higher accuracy of the movable axes in each direction could be attained. Figure 5 the linear motor installed in all 3-axis Mini CNC machine.

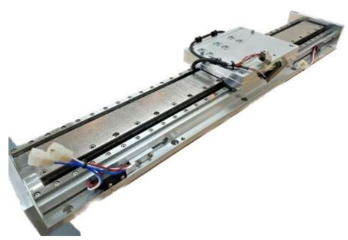

Fig.5 the linear motor

3 System implementation, Trial and Verification

After upgrading and retrofitting the machine system, the processes of testing performances regarding accuracy, positioning, runout, and cutting have been implemented to verify the increased efficiencies. The implementations and testing results are presented in the following sections.

3.1 Runout testing by the digital dial indicator.

Firstly, the preliminary plane displacements were tested with a digital dial gauge with a resolution of 0.01 mm. The coordinate axes distances in each direction are the X-axis from 0 to 200 mm, the Y-axis from 0 to 200 mm, and Z-axis from 0 to 100 mm, respectively. Figure 6 presented the measuring experiments on coordinate axes particular include the X, Y, and Z directions.

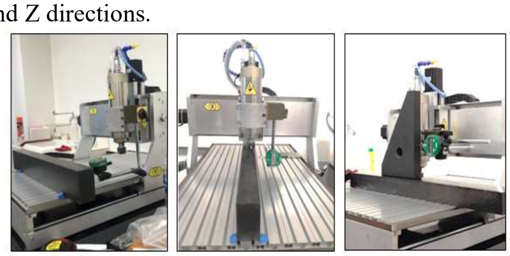

Fig.6 Measuring experiments on coordinate axes with a digital dial gauge

Table 2. Measurement result of X, Y and Z axis displacement using digital dial gauge

Items	Range	X axis		Y axis		Z axis	
		Before	After	Before	After	Before	After
1	0-200	0.52	0.04	0.45	0.05	0.56	0.05

3.2 Plane and inclination testing by Laser Interferometer

The method is that we use laser XT-80 machine have a high wavelength. Send light to reflect a reflector, which is attached to the tip of the axis of motion and look at the refraction of light when the light is reflected back to the XT-80 machine. We measure all 3 axes X, Y and Z axes by testing at a distance of 25 mm, divided into 4 ranges: 0-25 mm, 26-50 mm, 51-75 mm and 76-100 mm. See values before and after installing a new liner motor. That the new liner motor we installed have a good enough value

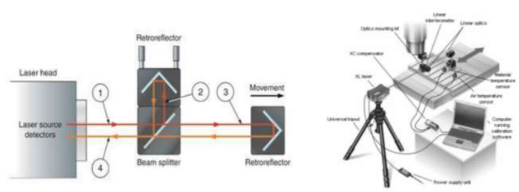

Fig.7 Measurement and reference using Laser interferometer

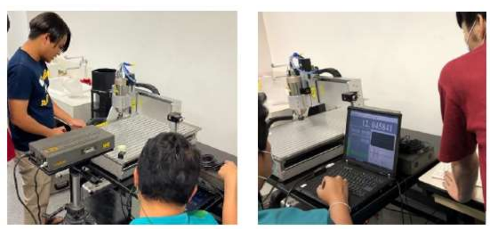

Fig. 8 Process setup Laser Interferometer

From the laser measurement, it can be seen that when we change the Ball screw drive to the Liner Motor drive. The values obtained from the movement are much more accurate as shown in the table 3.

Table 3. Measurement result of X, Y and Z axis displacement using laser check

Items	Range	X axis		Y axis		Z axis	
		Before	After	Before	After	Before	After
1	0-25	25.24	25.02	25.21	25.05	25.32	25.05
2	26-50	50.42	50.03	50.36	50.05	50.41	50.04
3	51-75	74.83	75.02	75.26	75.03	75.35	75.05
4	76-100	99.86	100.03	100.28	100.04	100.37	100.05

3.3 Balance testing by Ballbar system

The Ballbar test is used to measure the error caused by coaxial movement during the movement of the X-Y, Y-Z, and X-Z axes of the CNC machine and to check for inaccuracies caused by the controller and servo drive system. If the machine does not have any errors the plotted data is shown as a complete circle, indicating that the servo motor drives the X-Y, Y-Z, and X-Z drives with equal distances. But if the servo drive error has occurred, the circle will be distorted, e.g., by increasing the crest along the circumference and possibly making the circle more oval. Deviations from perfect circles reveal problems and inaccuracies in numerical control, servo drives and machine axes [5]. During data collection, the Ballbar moves in clockwise and counter-clockwise directions through a 360° data acquisition arc. Figure 9 illustrates the Ballbar Test method and Figures 10, 11, and 12 show the measurement results of before and after machine improvement.

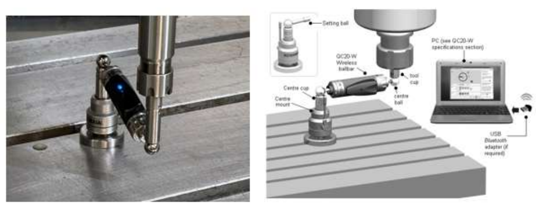

Fig.9 Shows how to measure with BallBar Test method.

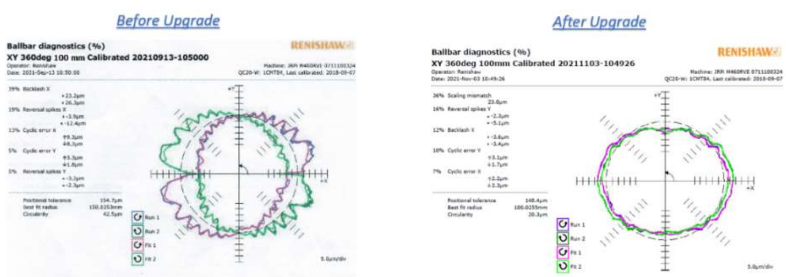

Fig.10 Measured results of X-Y axes before and after improvement

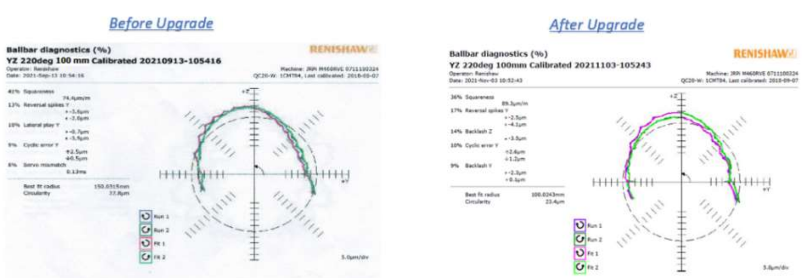

Fig.11 Measured results of Y-Z axes before and after improvement

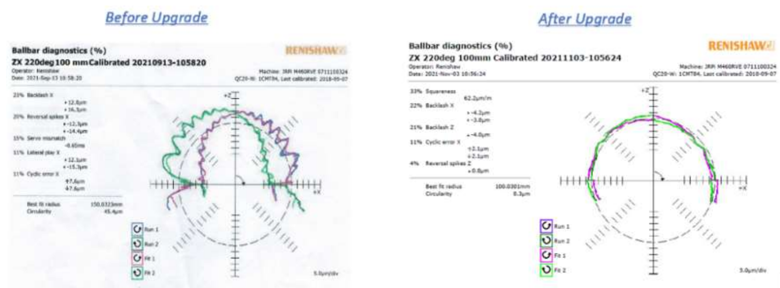

Fig.12 Measured results Z-X axes before and after improvement

3.4 Accuracy and position testing by experimental machining

The comparative machining experiments by before and after improvements of the mini CNC machine. The semicircular shape with diameter 90 mm. was machined for testing on simultaneous movements in the X-Y, Y-Z and X-Z axes, with same material, tooling, and cutting parameters. The semicircular shape milling tests are shown in Figure 13

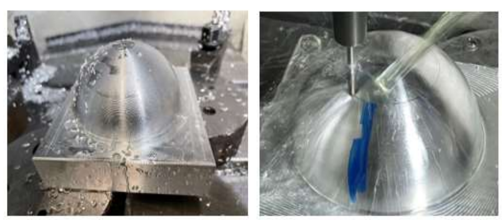

Fig.13 Shapes, dimensions and surface finishes of machined parts

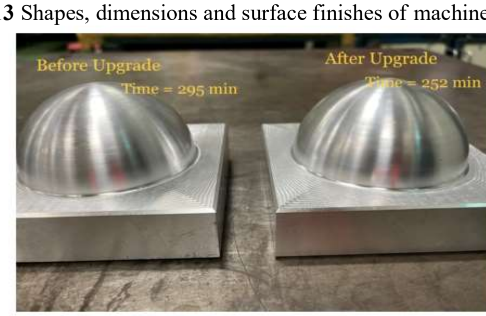

Fig.14 Comparative testing results of machined parts before and after upgradation of the mini CNC machine

4 Discussion

Mini CNC machine improved in this research by means of structural improvement design by using 7075 aluminum material as the main structure. Also, changed the main drive unit from a ball screw to a liner motor set has been implemented. The increased improvements can be obviously observed from the spindle motion experiments whether X-Y, Y-Z, and X-Z axes which are measured by dial gauge, laser, Ballbar, and machining, respectively. The machining results of semicircular specimens revealed that précised sizes and smooth and consistent surface roughness are better feasibly controlled with the upgraded mini CNC machine. Although the upgraded machine has weight heavier, the motion control during milling processes still obtained accurate positioning. Furthermore, the percentage errors of X and Y axes after improvements are less than 1% which is possibly satisfactory and acceptable for producing miniature parts. The machining time of the machine before adjustment took a total of 295 minutes, while the machine after adjustment took 252 minutes, indicating that it took 17% less time and the surface finish was much

5 Conclusion

In this paper, the mini CNC machine has been retrofitted to improve machining accuracy consisting of structural improvement and the X, Y, and Z axes drive unit replacements. The upgradation of the system is conducted by changing a traditional ball screw to a high-precision of linear motor system and replacing the structure from aluminum folding with strengthened solid aluminum. After qualified retrofit and well-alignments, the remarkable results of experimental measurements and machining tests illustrated the satisfaction of machine precision and performance. Thus, better dimensional accuracy and lesser vibration are capably achieved which leads to improving the motion control of axes movements and surface quality. Consequently, the miniature products are feasible to manufacture with the improved machine. The specific details and processes of retrofit and upgradation will be presented in a separate paper.

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