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ORIGINAL ARTICLE

Development and evaluation of the machining performance of a CNC gantry double motion machine tool in different modes

Abdul Hadi Jalaludin[1] · Mohd Hamdi Abd Shukor[2] · Noor Azizi Mardi[3] · Ahmed Aly Diaa Mohammed Sarhan[2] · Mohd Sayuti Ab Karim[4] · Seyed Reza Besharati[4] · Wan Nur Izzati Wan Badiuzaman[4] · Yusuf S. Dambatta[4]

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Abstract Conventional methods of building CNC machine tools involve using linear motors and ball screw drives to obtain table motion. The double opposite sync motion design is an improvement over traditional CNC machines. In this work, an enhanced CNC gantry machine design is proposed, which exhibits a double motion mechanism. The new design is based on a rack and pinion system such that both the gantry tool and worktable are movable. The gantry's natural frequency was designed at 202 Hz in the first vibration mode, enabling it to work at higher speeds of up to 11,530 rpm, which makes the gantry suitable for both rough cutting and fine finishing. A prototype of the multi-mode motion CNC gantry milling machine was developed to investigate the machining performance and efficiency of the double opposite sync system. Performance analysis was done using ball bar precision tests on the different modes of CNC gantry operation. Validation tests were carried out to determine the effects of the motion of the machine parts on the dimensional accuracy and surface finish of the machined parts. The results indicated that the straightness of the developed machine was reduced from 176.3 to 114.6 μm, which occurred due to the reduced total distance travelled by the tool and worktable. Moreover, the circularity increased from 338.7 to 667.0 μm. This increase could be attributed to the combination of errors arising from both the gantry and table.

Keywords CNC gantry · Double motion · Machining · Accuracy · Ball bar test · Backlash

✉ Wan Nur Izzati Wan Badiuzaman
wnezaty@gmail.com

[1] London, UK

[2] Kyoto University, Kyoto, Japan

[3] Royal Melbourne Institute of Technology, Melbourne, Australia

[4] Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

1 Introduction

Manufacturing applications using computer numerical control (CNC) machines have seen a huge rise in industry. The CNC machine consists of several components, such as the static beam, moveable beam, moveable worktable, adjustable gantry and overhead beams. The beams are the most significant parts of a CNC gantry machine because they are responsible for the motion, accuracy and performance of the machine. Recently, significant improvements on CNC machines have been made with the advent of microprocessors and intelligent machining techniques. As a result of its robustness, the CNC machine is used frequently to produce a variety of designed components [1, 2].

Historically, CNC machines were built to increase the accuracy and machinability of various engineering components. The kinetics of the CNC machine is such that it has an extended worktable and robotic manipulators that facilitate easier handling of the machining process. This highly precise robotic kinetics has made the process gain widespread acceptance. Besides, CNC machines are found to have a high degree of repeatability, accuracy and resolutions [3–5]. Even with the numerous benefits of CNC machines, they are still linked to limitations, such as precision errors and tolerance. Machining process accuracy is critical in fulfilling product specifications in terms of product complexity and tolerance. Moreover, the state of CNC machine tool accuracy has been observed to have a huge impact on the quality of the end product [6].

Machining errors lead to dimensional inaccuracies in the CNC process, which in turn directly affect the end product quality. Errors that occur in CNC machines vary according to their origin. These errors might be a result of table positioning, parametric settings, thermal response characteristics, geometric dynamics, machine geometric defects, vibrations or cutting tool wear [7, 8]. Many studies have been carried out to investigate and identify possible means of overcoming machining errors. Moreover, investigations have shown that errors are much greater when the travel distance of the CNC machine exceeds 100 m. This is due to the increase in the length covered and time taken to complete the operation [9].

The kinematics of a moving gantry system is such that it consists of two linear motors mounted along parallel slides. This enables the gantry to exhibit motions in tandem with the rack and pinion system. The speed at which the robotic arms of the CNC machine reach the pre-programmed point is of utmost importance. The results obtained by previous researchers have shown that the gantry mode of operation is the fastest among all CNC machine configurations. It can reportedly attain an optimum operational speed of up to 80 m/min [10].

Presently, there are two types of CNC gantry machines used in industry. The first type is characterized by a moving worktable and fixed gantry, while the second type is designed with a moving gantry and fixed worktable. The first type is mostly used in mould and dies industries, and its kinetics allows the worktable to move using a ball screw, providing a significant improvement in precision, distance covered and accuracy. This type of configuration has also been used in the machining of aerospace components with strokes exceeding 100 m [11, 12].

Several investigations have focused on improving the precision of CNC gantry machines while simultaneously decreasing machine size and cost. In this work, an improved design of a CNC gantry machine that works in multi-mode operation is developed. The proposed design functions such that both the gantry and worktable are moveable during machining operation. The precision and accuracy of the developed gantry model are also investigated.

2 Methodology

In this work, the circularity, squareness, scaling mismatch and straightness error were obtained for each mode of operation of the gantry machine. The measurements were taken on the CNC gantry milling machine at a spindle speed of 18,000 rpm. The gantry machine had a stroke along the *x*-axis of 700 mm, along the *y*-axis of 370 mm and along the *z*-axis of 200 mm. The machine settings, specifications and experimental conditions are tabulated in Table 1.

Table 1 Machine specifications

Mode	Stroke (mm)		
	X	Y	Z
Gantry	700	370	200
Double column	500	370	200
Both combined	1000	370	200
No. of motors	3 unit 1 kW	1 unit 1 kW	1 unit 1 kW
Spindle speed	18,000RPM		
Lubricant	Water		

The straightness error can be obtained using different techniques. The most commonly used methods are techniques of measuring displacement and angles. The displacement technique is easier and more straightforward. It involves directly finding the extent of deviation from the straightness error. The angle measuring technique involves obtaining the deviation from set angles using an angular reflector. After obtaining the deviation, the straightness error can be obtained using angular readings and the time taken to obtain each reading [10, 13, 14]. In this work, the displacement measuring technique of obtaining the straightness error is employed.

2.1 Machine settings and equipment

The gantry machine used in this investigation has three modes of operation: gantry mode, double opposite mode and static bridge mode. The CNC controller of the machine was designed based on the centroid MPU11 CNC measurement system, which is a PC-based system that facilitates easier analysis of the work. The CNC controller provides synchronous motion of the table along its axis (X1) and also the tool's axis (X2). The control is done so the robot moves along all three axes of the machine's G-codes without the need for complex programming algorithms. As such, the pre-programmed G-codes are sufficient to run on the hybrid machine without further modifications of the program. Figure 1 illustrates the different configurations of the CNC gantry machine. Depending on the relative motion existing between the table and the tool, the CNC gantry machine is further classified into three: fixed bridge design, gantry design and double opposite motion design.

2.2 Double opposite motion concept

In this mode of operation, the tool and machined component move in synchronous motion but in opposite directions, as shown in Fig. 2a. The proposed 3D model for the double opposite mode illustrated in Fig. 2b allows the worktable to travel only about 500 mm while the tool has no restriction and can