Analysis of the Structure Stiffness of the Gantry Milling Machine with Different Spindle Modules

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Abstract - *This study employed finite element analysis to investigate the structure stiffness of the gantry milling machine with different spindle modules. Three spindles with built-in motor, direct-driven with motor and gear-train transmission can be installed in the same sliding ram head stock. The influence of the spindle modules on the stiffness of milling machine was analyzed. Current analysis results show that the built-in spindle head without the water jacket causes less deformation of crossbeam, less than 6% as compared with the other two machines. In addition, the three spindle modules show similar ability to resist the cutting force in X and Y directions. This study verifies that the sliding ram head can be used in gantry milling machine to accommodate multiple spindles system, which is favorable for customized design to meet various machining process.*

Key Words: Gantry milling machine, Linear guide, Structure stiffness, Motorized spindle,

1. INTRODUCTION

Gantry CNC milling machine has been widely used in processing of large workpiece and complex components because of its heavy-duty loading capacity and larger feeding strokes in machine frame [1]. Recently, to meet the increasing demand for special specifications and applications of machine tools in manufacturing industry, machine tool factories have developed different gantry machines with different machining performance. But the machining performance and efficiency are greatly determined by the spindle tooling system, depending on the necessity of heavy and rough machining or high speed and high precision machining [2], in addition to the structure characteristics of the machine frame and the feeding mechanism. For rough and heavy machining, spindle is operated at low speed and higher torque. Under this condition, a gear-trained spindle unit is mostly used. While, a high speed spindle is required for high speed finishing machining. Normally high speed spindle can be designed with built-in motor or driven directly by coupling with motor. The spindle module with different driven power is normally designed into different construction to be mounted in the head stock [3].

Basically, the gantry structure is the main load-bearing construction of the milling machine. The structure characteristics directly affect the performance of the milling machine. Especially, the sliding ram associated with spindle tool system, which is mounted on the crossbeam of gantry structure, is main component affecting geometry accuracy of the milling machine as well as the milling precision [4, 5]. Therefore, understanding the static and dynamic characteristics of the gantry structure under the influence of the spindle tooling system is of importance for improvement of the design of milling machine to enhance the machining performance [6]. Regarding the approach for analysing the structure performance with optimization design, finite element method has been considered a powerful approach, as the application in machine tools [7-9].

The main purpose of this study is to investigate influence of the spindle module on the static characteristics of a gantry milling machine by finite element modelling approach. The gantry milling machine was designed to accommodate the spindle tool module of different design specification, which probably affects the structure characteristics of gantry machine. Analysis results are expected to provide a reference for the design improvements of the gantry structure with desired performance.

2. FINITE ELEMENT MODELLING

2.1 Construction of gantry machine

Fig-1 illustrates the solid model of a gantry milling machine, including two vertical columns, crossbeam, saddle stock and sliding ram with spindle head. Basically the structural modules of the machine frame are made of cast iron. The saddle stock is mounted on crossbeam by a hybrid guideway systems, in which the upper guideway is composed on three linear roller guides and the lower guideway is constructed with sliding contact surface coated with Turcite–B antifriction layers. The hybrid guideway provides the feeding motion with low friction, high precisions and high rigidity [10]. The spindle ram is supported in the saddle stock and fed by twin ball screws driven mechanism. The guideways of the spindle ram are also constructed with sliding modules coated Turcite–B antifriction layers.

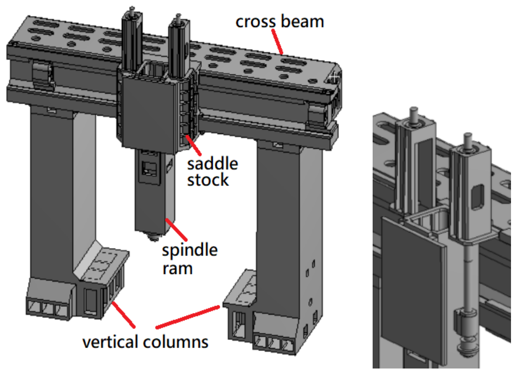

Fig -1: Construction of gantry milling machine.

Three type of milling spindle systems, including built-in motor (motorized) spindle (123kg, 18000rpm, 25Kw), direct-driven spindle (277kg, 12000rpm, 26Kw) and gear-trained spindle (410kg, 6000rpm, 26Kw), as shown in Fig-2, can be installed in the feed ram, according to the requirement for different machining purposes.

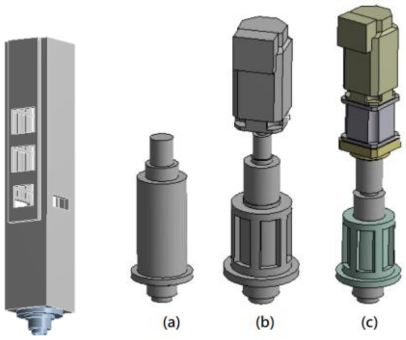

Fig-2: Sliding ram stock installed with (a)motorized spindle, (b)direct-driven spindle, (3) gear- trained spindle.

2.2 Finite element models

To evaluate the structure performance of the gantry milling machine with different spindle system, the finite element method was employed to modeling the gantry machine for assessment the static characteristics. The commercial finite element analysis software code ANSYS 16.0 was used for the modeling of the milling machine. The finite element model of machine structure is shown in Fig-3. Each structural component of the system was meshed using eight-node hexahedron element, with a total of 112,100 elements and 327,727 nodes. The linear guide modulus were included in the finite element model since they were demonstrated to affect the mechanical behaviors of the spindle heads. In this study, the influence with the different spindle system on the structural stiffness was mainly concerned. Therefore, the effects from the contact interfaces of the guideway mechanism were neglected and hence these interfaces were assumed at fully bonded state. Also the spindle-bearings were not included in the spindle model by modeling the spindle unit as a cylindrical part with similar geometry features.

Materials used for the all structures and components are gray casting iron for machine frame, carbon steel for other supporting components such as motors and bearings supports, and steel alloy for linear components and spindle unit. Mechanical properties of these different materials used in the finite element analysis are summarized in **Table-1**. The boundary conditions were imposed on the bases of the two vertical columns. The loading conditions associated with analysis modes, as shown in Fig-3, were given as follows:

(1) Static analysis under gravity forces, without any external force.

(2) Static analysis under external force of 2138 N applied at the spindle head nose in X, Y and Z directions, respectively.

Table-1: Mechanical properties of structure materials

Material	Gray cast iron	Carbon steel	Steel alloy
Density (g/cm^3)	7.3	7.85	7.85
Young modulus (GPa)	124	205	205
Poisson's ratio	0.27	0.29	0.32

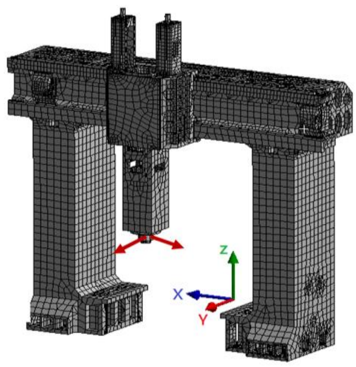

Fig-3: Loading conditions applied on spindle nose in X and Y directions respectively.

Here, the force was intended to simulate the cutting forces generated under the cutting on carbon steel with carbide face milling cutter with diameter (*D1*) of 100 mm and cutting edge (*z*) of 4. Cutting conditions are: cutting depth (*ap*, 3mm), cutting speed (V_c, 285m/min), spindle speed (*n*, 726rpm) radial cutting width (*ae*,100mm) and chip load(f_z, 0.28). The cutting force F_t can be related to cutting conditions based on the following formula [11],

$$\text{Cutting speed (m/min)},\ v_c = \frac{\pi \cdot D_1 \cdot n}{1000} \tag{1}$$

$$\text{Feed rate (mm/min)},\ v_f = f_z \cdot z \cdot n \tag{2}$$

$$\text{Power (kw)},\ P_c = \frac{ap \cdot ae \cdot v_f \cdot k_c}{60 \cdot 10^6 \cdot \eta} \tag{3}$$

$$\text{Torque (Nm)},\ M_c = \frac{P_c \cdot 30 \cdot 10^3}{\pi \cdot n} \tag{4}$$

Cutting force (N), $F_t = \dfrac{1000 \cdot M_c}{D_1/2}$ (5)

In above, η is the power efficiency (80%) and k_c is the specific cutting force which is rated at 1730 (MPa) for part material of medium carbon steel [12], as seen in **Table-2**. Based on the machining conditions, the cutting forces was caudated as 2183 N.

Table -2: Specific cutting force K_c Value [12]

Workpiece Material	Tensile Strength (MPa)	Specific Cutting Force K_c (MPa) under different chip load in machining (mm/tooth)		
		0.1	0.2	0.3
Mild Steel	520	2200	1950	1820
Medium Steel	620	1980	1800	1730
Hard Steel	720	2520	2200	2040
Tool Steel	670	1980	1800	1730
Tool Steel	770	2030	1800	1750
Chrome Molybdenum Steel	770	2300	2000	1880
Chrome Molybdenum Steel	630	2750	2300	2060
Chrome Molybdenum Steel	730	2540	2250	2140
Chrome Molybdenum Steel	600	2180	2000	1860

3. RESULTS AND DISCUSSIONS

Fig-4 illustrates the deformation of the gantry milling machines with motorized spindle under the self-weight. It can be found from the figure that the crossbeam associated with the spindle ram module was deflected greatly by the gravity forces of these components on crossbeam. The maximum deflection of the milling gantry is 195.8 µm, in which the deflection of the crossbeam and spindle unit is 110.39 and 155.8µm, respectively. Essentially, the deformation of the crossbeam and spindle ram module will affect the geometrical dimension accuracy of the whole machine and motion precision of spindle tool. Therefore, it should be carefully adjusted by technician during assemblage process. For the machine with direct-driven spindle and gear-trained spindle, the maximum deflection of the cross bean with spindle ram is about 202.8 and 245.4 µm, respectively. This reveals that the deflection of the crossbeam with spindle ram stock slightly differs when different spindle module was installed on the crossbeam. Also, the spindle tool of built-in motor has less influence on the structure stiffness.

Fig-5 illustrates the bending deformations of the gantry milling with motorized spindle under the specific loading conditions. As observed, the sliding ram of the spindle module is greatly deformed due to lateral bending effects of the force that is respectively applied at the bottom of spindle head stock along X, Y and Z directions. The maximum deformation of the spindle under simulated cutting force in X, Y and Z directions is 39.7, 48.7 and 11.5 µm, respectively. The static stiffness of milling spindle in X, Y and Z directions is calculated as 54.99, 45.38 and 189.83 N/µm, respectively. The results show the gantry machine has higher stiffness in Z axis than in other directions.

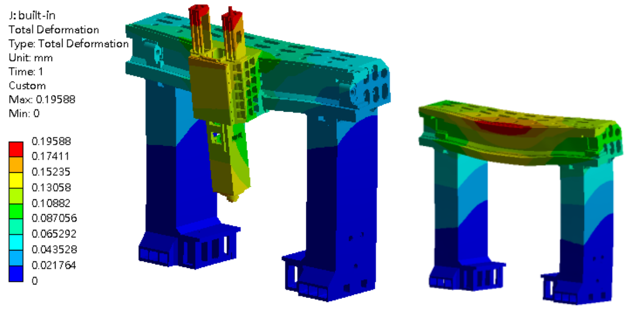

Fig-4: Deformation of the gantry milling machines with motorized spindle under the self-weight.

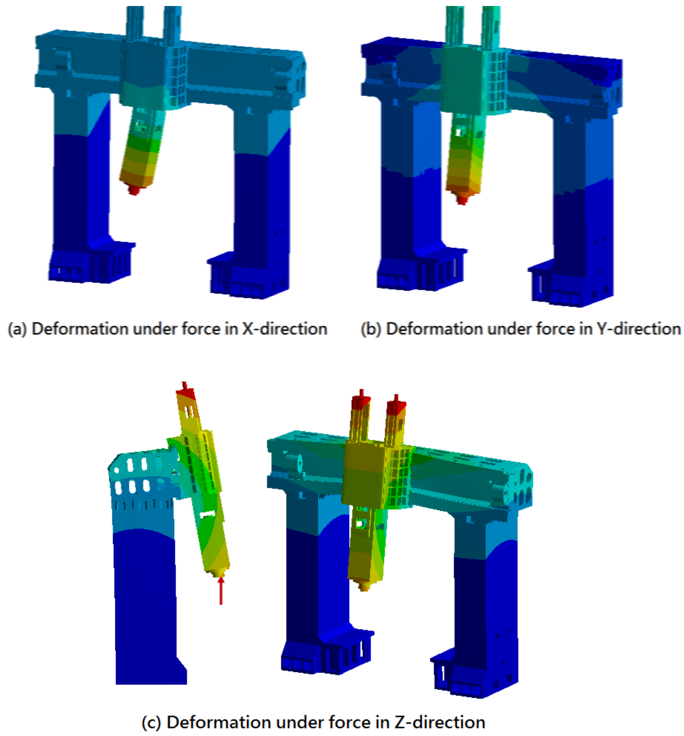

Fig-5: Deformed shape of the gantry milling under specific force in X and Y directions, respectively.

For the machine with direct-driven spindle and gear-trained spindle, the deformation of the spindle nose under different loading condition are calculated by using the same approach. The results are listed in **Table-3**. The static stiffness of the spindle nose under different loading directions were calculated for comparisons. It is found from **Table-3** that there is no significant difference in the stiffness among the milling machine with different spindle modulus. For milling machine with motorized spindle, the static stiffness in X and Y direction is higher than the other two machine modes, approximate higher than 6%. However, the gear trained spindle has highest Z-directional stiffness. This can be ascribed to the fact that the gear transmission mechanism also makes a contribution to a part of the structural stiffness in axial direction. Current results verify that the gantry machine can be equipped with different spindle module according to the requirement of machining process without affecting the structure performance to some extent. The sliding ram head can be used in gantry milling machine to accommodate multiple spindles system, which is favorable for customized design to meet various machining process.

Table-3: Deformation and stiffness of gantry milling with different spindle modulus

	Deformation, (μm)		
Spindle type	X-direction	Y-direction	Z-direction
Motorized	39.7	48.1	11.5
Direct driven	42.6	50.8	11.2
Gear trained	41.2	47.8	9.8

	Static stiffness, (K/μm)		
Spindle type	X-direction	Y-direction	Z-direction
Motorized	54.99	45.38	189.83
Direct driven	51.24	42.97	194.91
Gear trained	52.99	45.67	222.76

4. CONCLUSIONS

This study employed finite element analysis to investigate the structure stiffness of the gantry milling machine with different spindle modules. The spindle can be driven by different power transmission method, such as built-in motor, direct driven with motor and gear train transmission. Current analysis results show that the use of different spindle transmission methods has an impact on the rigidity of the spindle head under specific cutting force. According to the analysis results, it can be found that the built-in spindle head without the water jacket has a less influence on the deformation of crossbeam and show better rigidity in vertical direction, while the gear-trained and direct-driven spindle head with water jacket have lower rigidity. The rigidity difference is less than 6%. Regarding the static stiffness, the three spindle modules show similar ability to resist the cutting force in X and Y directions. This study also shows that the use of a water jacket will cause differences in the rigidity of the spindle head. Through the finite element analysis, it is confirmed that the same spindle head can be used in gantry milling machine with multiple spindles of different driven method and show a consistent structural rigidity.

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