Design of a bespoke five-axis CNC machine tool for machining thin-walled cylindrical components with internal concave circular arc surfaces

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Abstract

In this paper, bespoke design of a five-axis machine tool is presented for machining thin-walled cylindrical components with discontinuous internal concave circular arc surfaces, which addresses the challenge of discontinuous precision cutting at internal surfaces. The three jaw chuck is adopted to clamp the workpiece and thus gain its rotary motion in machining. A standard centre rack is used to support the rotational workpiece. Machining is undertaken by using an angle head bespoke designed, which is also installed in the electric-driven milling spindle of the cross slide. Axial movement of the milling cutter is obtained by the ball screw driven cross slide. To control the multi-axis motions, a standard CNC system is adopted and it enables the intermittent cutting of the non-continuous internal circular surfaces at the component. The performances of the machine tool have been evaluated through static, dynamic and harmonic response analyses. The machining trials are carried out using the bespoke designed machine, and the results show that the machine can realize the intermittent precision machining of the components with the machining accuracy as required.

Introduction

With the advance of machine tool technology in recent years, many kinds of CNC machine tools in different structural formats or configurations have been emerging, and widely used in aerospace, automotive, die and mold, and

shipbuilding industries [1]. More stringent requirements for CNC machine tools are put forward in aerospace manufacturing because aerospace structural parts are increasingly characterized with poor rigidity, easy deformation, thin walled, and complex machining features. One of the essential needs for the machine tool is to have good machining reachability, which means that the machine can reach the designated area to complete the machining of complex features.

To reduce the weight, magnesium alloy components with discontinuous internal circular arc structures are designed and popularly used in aerospace industry, as illustrated in Figure 1. Because of their limited reachability, standard commercial machine tools including CNC lathe and machining center as illustrated in Figure 2, cannot cope with the component machining requirements particularly with such a kind of structures as illustrated. At present, there are some typical problems during machining those components, including:

(1) An ordinary CNC lathe is modified and transformed to machine discontinuous internal concave circular arc surfaces. The rotational motion of the workpiece is realized by manual operations. During the machining process, two workers are required to cooperate on the lathe, which wastes the human resource. Furthermore, the proportion of unqualified products is relatively high because of the workers' inappropriate operations on the machine.

(2) Using the transformed lathe causes lower automation level. The longer the machining time takes, the lower production efficiency is.

(3) Before the machining process, a tool-room worker is often needed to use a scriber to mark lines on the workpiece to determine the processing location. Process parameters are set up relying on individual worker’s experience. Machining precision has been influenced by the operation personnel, which is not beneficial to the standardization of the production process and determinative quality control.

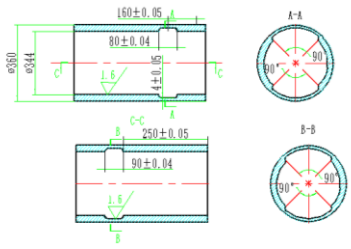


Figure 1: The component sketch

Figure 2: Standard CNC machine tools [2-4]

In this paper, development of a bespoke precision machine tool based on the innovative concept of enabling discontinuous cutting is presented, which aims to resolve bottleneck problems in the component production above. The focus will be on the holistic design methodology for the machine specifications and configurations, and development of key machine elements, although static and dynamic analysis of the machine tool will also be covered.

2 Design configuration and structure of the machine tool

In recent years, design research on machine tools has focused on error compensation, tool path generation, machine modeling and analysis, design of precision machine tools, machine tools for large structures and components, and machine tool design for high-speed machining [5-8], and good and encouraging results have been achieved. Configuring a reasonable structure of the machine tool will be the starting focus of this development. One of the motion axes of the machine must have sufficiently large feed depth. When the cutter reaches the specified position, the workpiece can also make a circular motion. The design configuration and structure of the machine tool as shown in Figure 3 is proposed in an innovative manner.

Figure 3 illustrates the key elements of the machine tool, which include the headstock (element 1), center rack (element 2), angle head (element 3), rotation spindle (element 4), cross slide (element 5), and the machine base (element 6), etc. The machine tool has three linear motion axes (X, Y, Z directions), one rotational axis (B axis), and one spindle axis. The role of the angle head is equivalent to the extension of the axial feed depth of the spindle, and the milling process along the radius direction can be implemented. The bespoke machine tool contains five motion axes, and their motions are controlled by a CNC system.

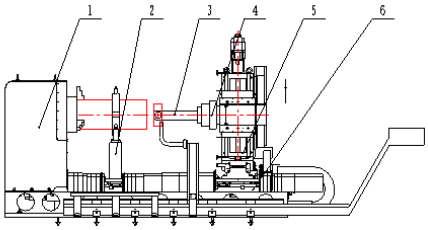


Figure 3: Design configuration and structure of the machine tool

The overall design concept is that workpiece is fixed by three jaw chuck, and supported by the center rack. The axes of the workpiece and machine tool are kept co-axial by adjusting the center rack. The angle head is used to convert the rotational motion of the spindle to motion of the milling cutter being installed at the tool shank of the angle head, and the direction of motion is transformed a 90°. The movement of Y axis is driven by ball screw installed in the machine base. The movement of X, Z axes is driven by ball screw installed in the cross slide. The movement of B axis is driven by the motor of the headstock. Therefore, discontinuous internal concave circular arc surfaces can be machined by the milling cutter.

Driving forces for X, Y, and Z axes are provided by the screw nut mechanism, and three grating rulers which have ±5μm precision are adopted to ensure the precision of positioning and repositioning. In exactly same way, one circular grating which has ±15″ precision is adopted to ensure the precision of rational motion.

3 Development of key machine elements

3.1 Design configuration and selection of servo motors

In order to ensure the normal movement of the five motion axes, appropriate servo motors are required to provide sufficient torque and power. The factors that need to be considered in the selection of the motor include the motor load, cutting force, transmission efficiency, ball screw pitch and diameter, the reduction ratio of the reducer, and the moment of inertia, etc [9]. The motor torque is calculated by using Equation (1). The moment of inertia at the ball screw is calculated by following Equation (2). The moment of inertia of linear motion components is calculated by using Equation (3). The moment of inertia for the coupling is given by reference manual. The moment of inertia for the motor load is the sum of the moment of inertia of the ball screw, the linear motion components and the coupling. The required servo motor can be decided by the comprehensive consideration of motor torque and the moment of inertia of motor load.

$$T \times R \times 2\pi \times \mu = (F + f) \times \frac{b}{1000} \tag{1}$$

$$J_b = \frac{\pi}{32} \times \rho \times l \times D_b{}^4 \times \frac{1}{R^2} \tag{2}$$

$$J_L = m \times \left(\frac{b}{2\pi \times R}\right)^2 \tag{3}$$

In Equation (1), T indicates motor torque, R indicates the reduction ratio of reducer, μ indicates transmission efficiency, F indicates the force of motor load, f indicates cutting force, and b indicates ball screw pitch.

In Equation (2), J_b indicates the moment of inertia of ball screw, ρ indicates the density of ball screw, l indicates the length of ball screw, D_b indicates the diameter of ball screw, R indicates the reduction ratio of reducer.

In Equation (3), J_L indicates the moment of inertia of linear motion components, m indicates the quality of linear motion components, b indicates ball screw pitch, R indicates the reduction ratio of reducer.

Through the above configuration process and calculations, the motors are selected and listed in Table 1.

Table 1: The motors selected

Axes	X axis	Y axis	Z axis	B axis
Rated power (KW)	3.1	5.2	3.1	3.8
Rated torque (N·m)	20	36	20	16

3.2 Design of the cross slide

In order to machine the specific areas as highlighted in Figure 1, the path of the milling cutter should be realized by arc interpolations, and hence the structural forms of X, Y, and Z axes are designed.

The movement of X axis and Z axis is provided by the cross slide. In this development, a standard cross slide is selected according to the requirements of the movement range and cutting forces. The cross slide includes X and Z slides, tank chain, servo motor, etc.. Two displacement sensors are respectively installed to limit the extreme motion positions of X and Z axes. Furthermore, four mechanical blocks are also installed to limit the physical extreme position.

Taking into account the dimensions of the workpiece, the designed strokes of X and Z axes are 580 mm and 410 mm respectively.

3.3 Design of the rotational spindle and angle head element

Rotational spindle provides the cutting power, as shown in Figure 4, in which 1 indicates the rotational spindle. Rated torque and power of the spindle motor is determined by cutting force, the diameter of the cutting tool, reduction of ratio, and safety efficiency. A standard rotational spindle with 5.2 KW rated power and 36 N.m rated torque has been selected through the design analysis.

Angle head element is a key structure for transmitting cutting force, as also shown in Figure 4, where 2 indicates the angle head, 3 indicates the tool shank, and 4 indicates the cutting tool.

Angle head's section is designed as a circular structure, and its effective length is 350 mm so as to ensure the enough length to reach the position of internal concave circular arc surfaces. Angle head developed is of 75 N.m output torque. A standard NT50 interface is adopted to connect the angle head and the rotational spindle. An effective positioning way is that the taper shank of the angle head is inserted into the taper hole of the spindle, and then angle head is fixed onto the end face of the rotational spindle by using screws. A standard BT50 interface, which is helpful to tool measurement by tool auto-checking instrument of NC workshop, is adopted to connect the angle head and milling cutter. The maximum clamping diameter of the milling cutter is 20 mm.

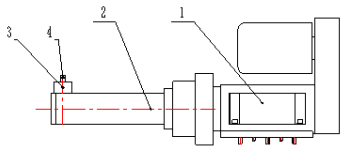


Figure 4: Rotational spindle

3.4 Development of the machine mechanical structure

The material selections for the machine mechanical structure and the associated design analysis are one of the essential design stages in determining the final performance of the machine, such as its temporal stability, specific stiffness, homogeneity, ease of manufacturing, and cost, etc [10].

Although there are a lot of structural materials available, only a few materials have been chosen to build the precision structure of machine tools. Cast iron has been widely used on industrial machine tools due to its low cost and reasonable damping characteristics [11]. Taking into account the factors of vibrations absorption, dynamic performance and engineering life, grey cast iron has been chosen as the machine-base material, and the structure is obtained by casting. Furthermore, the casting process should be considered during the structure design.

The machine base is the main body structure of the machine tool. Headstock is installed on the end of the machine base. Two linear guides are mounted onto the machine base, and the cross slide driven by ball screw is installed onto the

guides. Two junk slots are mounted on both sides of the machine base. The overall dimensions of the structure design are 2,580 mm, 1,000 mm, and 350 mm in length, width, and height respectively.

3.5 Development of the control system

Computer numerical-control (CNC) was introduced into machine tools industry in the early 1970s, and since then many companies have designed their own control systems for machine tools [11]. In this development, a CNC system (SIMENS 828D) has been chosen to control the axis motions and implement signal transmissions on the machine.

3.5.1 Hardware system

The main hardware system consists of standard CNC controller, control panel, hand wheel, input and output module, power module, motor module, spindle servo motor, feed servo motor, absolute rating ruler, absolute circular grating and 24V switching power supply, etc. The CNC system is the control center of the machine, transmits instruction to machine tool, and drives machine tool axes and actuations.

Electrical components including the encoder interface module, power module, motor module, reactor, transformer, isolating switch, and pneumatic switch, etc. are all installed into the electric control cabinet, and wired according to the electric principle design diagram. The design diagram mainly consists of the power supply diagram, connection diagram of CNC system and peripheral devices, and PLC inputs and outputs diagram, etc.

Taking into account of the substantial heat produced by electrical components, an air conditioner is also installed to ensure constant temperature in the control cabinet.

3.5.2 Software system

(1) Setting of the machine data

The machine data is simplified as MD. The adjustment, configuration and function realization of the CNC system are achieved through the setting of machine data. It mainly contains the following aspects:

- General MD for the system setting, offset setting, driving data and system memory allocation, etc.
- Channel MD for the management of a particular channel of the program operation, such as the allocation of the axis channel, etc.
- Axis MD for the parameters setting of each axis at the machine tool, such as given value and actual value setting, feed axis setting, and the spindle setting, etc.

- Driving MD for the parameter setting of motors, and the drive optimization of motors, etc.

(2) PLC programs design

Information exchanges among the CNC system, peripheral equipment, and different components such as control panel, handheld unit, limit switches, alarm instructions, etc. are achieved by PLC programs. PLC programming based on SIMATIC S7-200 has been developed by using the method of ladder diagram programming.

4 Performance analysis of the machine tool

In order to meet the design requirements, the bespoke machine tool must have good static stiffness and dynamic performance. The static stiffness represents the ability of machine to resist deformation, and reflects the stability of machine. The dynamic performance of the machine tool reflects the fundamental vibration mode shapes, corresponding frequencies, and vibration characteristics under the effect of the external excitation force.

The static stiffness and dynamic performance of the machine tool have an important influence on the precision and quality of a product. The FEA method is used to evaluate the performance of bespoke machine tool from static, modal, harmonic response and thermal analysis. A 3D FEA model has been established. The mesh is generated by using tetrahedral elements. The freedoms of the base bottom are constrained, then FE calculations have been carried out. Material properties used in the FEA are listed in Table 2.

Table 2: Material properties used in FEA

	Density (Kg/m^3)	Elastic modulus (GPa)	Poisson's ratio	Conductivity ($W \cdot m^{-1} \cdot ℃^{1}$)	Specific Heat ($J \cdot kg^{-1} \cdot ℃^{1}$)	Expansion ($10^{-6} \cdot ℃^{1}$)
Cast iron	7800	125	0.28	40	460	10
Steel 45	7850	200	0.3	44	460	11.59
40Cr	7900	210	0.3	44	460	11.9

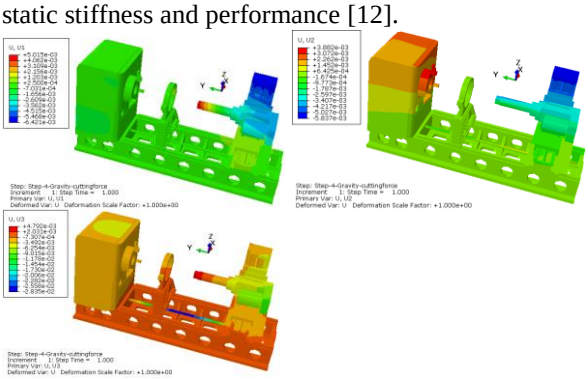
4.1 Static analysis

The static analysis of the machine tool is mainly to calculate the response of the machine under the condition of the static load, and the displacement, stress and strain of the machine tool can be obtained. When the machine is subjected to static force, the governing equation between force and deformation can be written as:

$$\{F\} = [K]\{x\} \qquad (4)$$

Where $\{F\}$ represents the overall static load vector of machine tool structure, $[K]$ represents the whole static stiffness matrix of machine tool structure, $\{x\}$ represents the overall displacement vector of machine tool structure.

The static response of the machine tool under the coupling of gravity and cutting force is analyzed. Cutting forces of 350N in three directions were applied to the position of tool center point. Gravity acceleration g is 9.8m/s^2. The overall structural deformation is shown in Figure 5. The maximum displacements in X, Y, Z directions are 6.421×10^{-3}mm, 5.837×10^{-3}mm, 2.835×10^{-2}mm respectively, and the static stiffness in X, Y, Z directions is 55N/um, 60 N/um, 12 N/um accordingly. Due to the large slenderness ratio of the screw, a large displacement of 2.835×10^{-2}mm has been caused by its self-weight in Z direction, which results in the fact that the static stiffness in Z direction(X-Y plane) is less than *Y* direction(X-Z plane) and X direction(Y-Z plane). The maximum displacements at tool center point in X, Y, Z directions are 4.322×10^{-3}mm, 2.034×10^{-3}mm, 3.852×10^{-3}mm respectively, and the static stiffness in X, Y, Z directions is 81N/um, 172 N/um, 91 N/um accordingly. Because the displacement at tool center point will directly affect the dimensional precision and surface quality, it's necessary to pay more attention to tool center point. The magnitude of deformations at tool center point is at the micron level, therefore machining accuracy can be ensured. It can be found from the results listed in Table 3 that the machine tool has good static stiffness and performance [12].



(a) X direction (b) Y direction (c) Z direction

Figure 5: Statics and deformation analysis of the machine tool

Table 3: Static deformation and stiffness

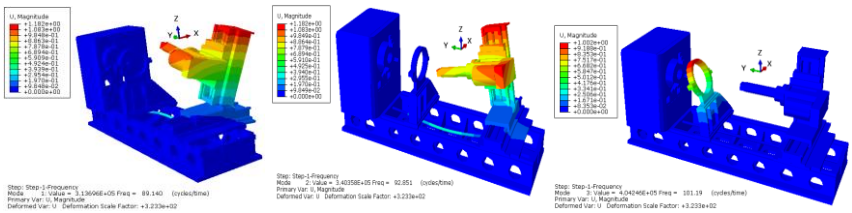
	Deformation(mm)			Stiffness(N/um)		
	X direction	Y direction	Z direction	X direction	Y direction	Z direction
Machine tool	6.421×10^{-3}	5.837×10^{-3}	2.835×10^{-2}	55	60	12
Tool center point	4.322×10^{-3}	2.034×10^{-3}	3.852×10^{-3}	81	192	71

4.2 Modal analysis

Modal analysis belongs to a typical dynamic problem of undamped free vibration, and it can be used to understand the characteristics of different mode shapes, find the weakness of the structure, optimize the design, and determine the frequency range of the harmonic response analysis. The number of modal order mainly depends on external excitation frequency. Generally, the first ten mode shapes of the machine tool are analyzed, which is enough to reflect the vibration characteristics of the machine tool. During the cutting process, the natural frequencies of higher order modes are much higher than the frequency of excitation force. The first ten natural frequencies and the description of the mode of bespoke machine tool are extracted and shown in Table 4. The first three vibration modes are shown in Figure 6.

Table 4: First ten natural frequencies

Mode no.	Frequency(Hz)	Description of mode
1	89.14	The combined deformation of cross slide and ball screw
2	92.85	The combined deformation of cross slide and ball screw
3	101.19	The deformation of center rack
4	106.33	The deformation of ball screw
5	107.08	The deformation of ball screw
6	108.20	The deformation of ball screw and headstock
7	111.78	The deformation of headstock
8	211.83	The deformation of headstock
9	227.26	The deformation of cross slide
10	229.55	The deformation of headstock



(a) The first mode (b) The second mode (c) The third mode

Figure 6: First three natural frequencies and mode shapes of the machine

The working frequency of the machine tool is less than 30Hz, and the lowest natural frequency of the machine tool is 89.14Hz. Therefore, the working frequency of the machine is far away from the natural frequency. Machine vibration mode shapes in the first ten natural frequencies occurred mainly in the cross slide, the headstock and the ball screw, where the vibration numbers of the cross slide are three times, the vibration numbers of the headstock are four times, and the vibration numbers of the ball screw are five times. The most

vibration numbers occurring in the ball screw attribute to its larger slenderness and poorer rigidity.

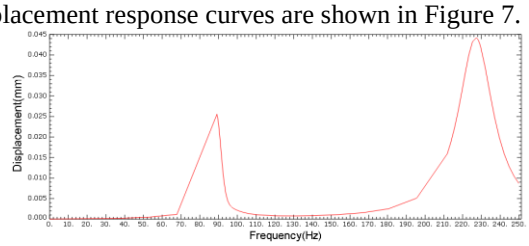
4.3 Harmonic response analysis

The harmonic response analysis is used to determine the linear structural response under the condition of harmonic forces. The steady-state response is only considered during the analysis. The structural vibration response is able to be predicted, and resonance frequency can be found in order to avoid harmful effects.

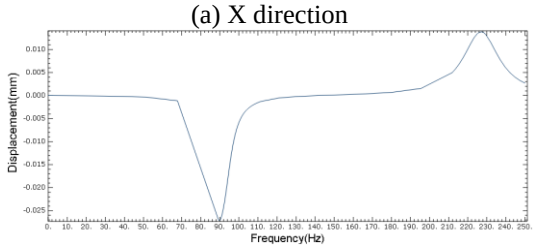
In this analysis, cutting forces *F* acting between workpiece and cutting tool was adopted as harmonic forces and applied to the machine.

$$F = F_0 \sin(\omega t) \qquad (5)$$

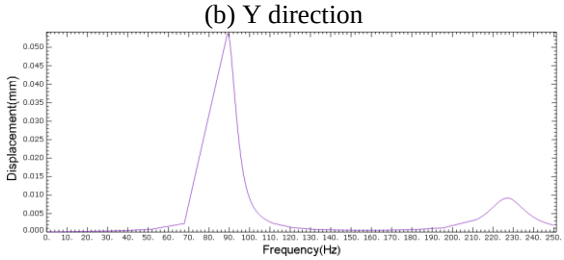
An amplitude F_0 of 350N was assumed and a frequency range from 0 to 250Hz according to Table 4 was chosen to analyze harmonic response. The frequency-displacement response curves are shown in Figure 7.



(a) X direction



(b) Y direction



(c) Z direction

Figure 7: Harmonic responses of the machine tool

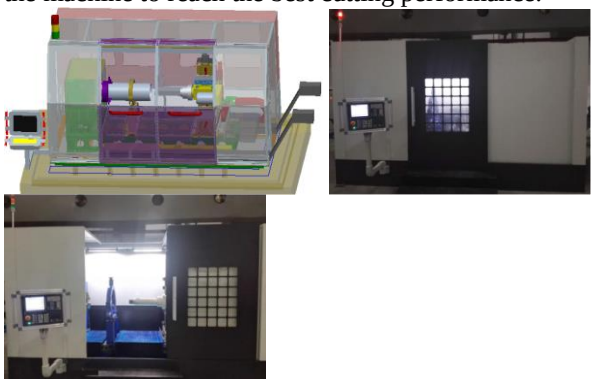
In Figure 7(a), the maximum response displacements of the machine tool in X direction are 0.044mm and 0.025mm, which corresponds to the frequencies of

228Hz and 90Hz respectively. In Figure 7(b), the maximum response displacements of the machine tool in Y direction are 0.027mm and 0.014mm, which corresponds to the frequencies of 90Hz and 228Hz respectively. In Figure 7(c), the maximum response displacements of machine tool in Z direction are 0.054mm and 0.010mm, which corresponds to the frequencies of 90Hz and 228Hz respectively. In addition, the vibration response displacement is very small when the frequency is less than 30Hz.

Through the above analysis, it can be seen that the first, second, the ninth, and the tenth mode shapes are the weakest. The maximum vibration deformations occur in cross slide and headstock at a frequency of 228Hz, and the maximum vibration deformations occur in cross slide and ball screw at a frequency of 90Hz. Since the working frequency of the machine tool is less than 30Hz, and far from its natural frequency, resonance won't occur. Therefore the machine tool has excellent dynamic performance.

5 Machine setup and experimental trial

The bespoke machine tool illustrated in Figure 8 has been utilized to machine some typical components. The sample is shown in Figure 9. A surface roughness *Ra* of 1.6um was got and dimensional accuracy reached ±0.02mm. The machining results illustrate that the bespoke machine tool has good performance and function. The actual products will be machined so as to make the machine to reach the best cutting performance.



(a) 3D design model of the machine (b) Machine assembly and setup

Figure 8: The bespoke machine setup

Figure 9: The machined sample

6 Conclusions

As the standard CNC lathe and CNC machining center are unable to accomplish the machining of some components with specific requirements as increasingly encountered in aerospace engineering applications, bespoke design and manufacturing of a five-axis machine tool is thus carried out particularly for machining thin-walled cylindrical components with discontinuous internal concave circular arc surfaces.

The holistic development of the bespoke five-axis machine tool has been completed on the basis of key machine elements design including the servo motors, cross slide, angle head, rotary spindle, machine base, and control system. The core design concept for the machine is to integrate the structure and design principle of the CNC lathe and CNC milling machine so as to realize the precision milling process of discontinuous internal concave circular arc surfaces by using a special reversing spindle device.

The performances of the machine tool have been evaluated through static, dynamic and harmonic response analyses, which shows that the machine tool has excellent static stiffness and dynamic characteristics.

CNC milling trials have been finished after the equipment debugging, and the results show that all machined components are qualified, and the precision can meet design requirement.

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