Design and Calculation of 2-Axis CNC Lathe Machine (Spindle and Shaft)

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Abstract - The main aim of this research paper deals with the design of spindle for 2-axis CNC lathe machine. The spindle axis is horizontal in lathe machine. The speed of spindle can be set with levers and pulley belts to give a range of speed. Especially, spindle assembly involves design of shaft diameter, spur gear, selection of bearing and keyway. The shaft is made with commercial steel and speed is 1500 rpm. The length of the shaft is 1000 mm and outside and inside diameter of shaft are 86mm and 60.2mm. In spur gear design, pinion and gear are made with cast iron. Module and face width of the spur gear are 5mm and 63mm. The dynamic force, wear force and endurance force of the spur gear are 5751.628N, 25512.820N and 7565.505N.

Indexed Terms - spindle, CNC Lathe, shaft, module, face width.

I. INTRODUCTION

Computer Numerical Control (CNC) is among the fastest growing fields in manufacturing today. The CNC technology was applied on basic conventional machines like lathes and milling machine. In 2-axis CNC lathe machine the main four portions are as follows:
1) Design of spindle assembly
2) Design of carriage and tool post
3) Design of bed-way and
4) Design of axis drive system

In this research paper is how to design of spindle assembly.

II. CNC MACHINE COMPONENTS

The controllable components of CNC machine are feed axis system, feed drive unit, machine work spindle drive unit, spindle chuck unit, tool turret and tool changer, tailstock and CNC control unit as shown in Fig. 1.

Fig. 1. CNC Lathe Machine [4]

III. SPINDLE DRIVE UNIT

Spindle assembly contain shaft, spur gear, bearings and key as shown in Fig. 2.

Fig. 2. Spindle Assembly

The work spindle generates workpiece rotation of turning lathe and tool rotation of milling and drilling machines. The spindle can be driven by a three-phase AC or DC motor. In three-phase AC drives spindle speed selection is obtained through the gearbox.
However, in most case the work spindle of CNC machines are driven by DC motors whose speed is infinitely variable by means of a tach generator.

Work holding equipment is provided to secure the workpiece to the work table (milling) or the spindle (turning). On turning lathe the jaws generally can be opened and closed by the NC program, and it is possible to set various clamping pressure. Since CNC machines are frequently work with very high speeds and since chucking pressure cannot be increased at will on account of workpiece distortion.

IV. FUNCTION OF MACHINE SPINDLE

A spindle may locate and hold the workpiece or the outer and rotate the same. A spindle is a shaft which mounted on bearing supported in the machine tool housing. In order to avoid deflection and run out, the spindle have to be well supported in true bearing. Any slackness in the bearings will clearly affect the location of the spindle.

V. MANUFACTURING PROCESS OF SPINDLE SHAFT

The spindle shaft is manufactured by pipe system. Stainless steel shaft up to 48 inches in diameter to be used as boiler headers and other high pressure purpose is made by forging and drawing. The hollow forging is then transferred to the draw bench, where it is placed over a mandrel and forced through a die to be reduced and elongated. Except for some size limitation, any casting or metal may be centrifugally cast.

a. Spur Gear Design

The calculation of spur gear is done as follow:

\[ F_t = \frac{9550kW}{\text{rpm}_p \times D_p / 2} \]  

(1)

Where, \( F_t \) = tangential force (N)  
\( \text{kW} \) = power (kW)  
\( \text{rpm}_p \) = speed of pinion (rpm)  
\( D_p \) = diameter of pinion (mm)

\[ v = \frac{\pi D_p \text{rpm}_p}{60} \]  

(2)

Where, \( v \) = pitch line velocity (m/s)  
\( S = S_o \times \left( \frac{3}{3 + v} \right) \) For \( v \) less than 10 m/s  
(3)

\[ S = S_o \times \left( \frac{6}{6 + v} \right) \] For \( v \) to 10 to 20 m/s  
(4)

\[ S = S_o \times \left( \frac{5.6}{5.6 + \sqrt{v}} \right) \] for \( v \) greater than 20 m/s  
(5)

\[ \left( \frac{1}{m^2 y} \right)_{all} = \frac{Sk\pi^2}{F_t} \]  

(6)

Where, \( m \) = module (mm)  
\( y \) = form factor (unitless)  
\( S \) = allowable tooth stress (N/m²)  
\( S_o \) = endurance stress (N/m²)  
\( b = k_{red} \pi m \)  
(7)

\[ k_{red} = k_{max} \times \left( \frac{1}{m^2 y} \right)_{ind} / \left( \frac{1}{m^2 y} \right)_{all} \]  

(8)

Where, \( b \) = face width (mm)  
\( k_{max} = 4 \)

\[ F_o = S_o b y \pi m \]  

(9)

Where, \( F_o \) = endurance force (N)  
\( F_w = D_p b K Q \)  
(10)

Where, \( F_w \) = wear force (N)  
\( Q = \frac{2D_g}{D_p + D_g} \)  
\( K \) = stress fatigue factor (kN/m²)
\[ F_d = F_t + \frac{21v(bc + F_t)}{21v + \sqrt{bc + F_t}} \]

(11)

Where, \( F_d \) = dynamic force (N)
\( c \) = deformation factor (kN/m)

b. Shaft Design
The equations for shaft design are as follows:
\[ M_1 = \frac{9550kW}{rpm} \]

(12)
Where, \( M_1 \) = tangential moment (Nmm)
\[ F_t = \frac{M_1}{D/2} \]

(13)
\[ F_t = F_t \tan \phi \]

(14)
Where, \( F_t \) = tangential force (N)
\( F_r \) = radial force (N)

ASME Code equation for hollow shaft with axial load,
\[
\frac{d_0^3}{\pi S_s(1-K^2)} = \frac{16}{K_b M_b + \frac{\alpha F_s d_0}{8}(1+K^2)} + [K_t M_t]^2
\]

Where, \( d_0 \) = outside diameter of hollow shaft (mm)
\( S_s \) = allowable shear stress (MN/m²)
\( K = \frac{d_1}{d_0} \)
\( M_b \) = bending moment (Nmm)
\( \alpha \) = column-action factor = \( \frac{1}{1-0.0044(L/k)} \)
\( F_s \) = axial force (N)
\( K_b \) = combined shock and fatigue factor applied to bending moment
\( K_c \) = combined shock and fatigue factor applied to torsional moment

Fig. 3. Result of Shaft Design

The outside and inside diameter of shaft are 86mm and 60.2mm.

c. Bearing Design
If a significant axial load is applied to a bearing along with a radial load, perform with the following steps:
1. Assume the value of \( Y \) from Table A.7. The value \( Y = 1.05 \) is reasonable, being about the middle of the range of the possible values.
2. Compute \( P = XV F_r + YF_a \).
3. Compute the required basic dynamic load rating \( C \).
4. Select a candidate bearing having a value of \( C \) at least equal to the required value.
5. For the selected bearing, determine \( C_0 \).
6. Compute \( F_a / C_0 \).
7. From Table A.7, determine \( e \).
8. If \( (F_a / V F_r) < e \), then \( X \) and \( Y \) value from Table A.7.
(9) If the new value of Y is different from that assumed in step 1, repeat the problem.

(10) If \((F_a / VF_r) / e\) use equation \(P = VF_r\) to compute \(P\) and proceed as for a pure radial load.

d. Key Design
The calculation of key is done as follow:

Key in shear,
\[
T_s = S_s \times B \times L \times d_o / 2
\]
(16)
Where, \(T_s\) = the shaft torque that the key can sustain from the stand point of shear (Nmm)
\(S_s\) = shear stress \((0.6S_y/F.S) (N/mm^2)\)
\(B\) = width of key (mm)
\(L\) = length of key (mm)
\(d_o\) = outside diameter of shaft (mm)
\(S_y\) = yield stress \((N/mm^2)\)
\(F.S\) = factor of safety

Key in compression,
\[
T_c = S_c \times (t/2) \times L \times (d_o / 2)
\]
(17)
Where, \(T_c\) = the shaft torque that the key can sustain from the stand point of compression (Nmm)
\(S_c\) = compressive stress \((S_y/F.S) (N/mm^2)\)
\(t\) = thickness of key (mm)
\(L\) = length of key (mm)
\(d_o\) = outside diameter of shaft (mm)

\(L_s = 0.877mm\) and \(L_c = 2.105mm\)

Design key length is less than gear face width .Thus choose key length=63mm.

e. Deflection of Spindle Axis
The total deflection of spindle nose consists of:

(1) Deflection \(y_1\) of the spindle axis due to bending forces \(P_1\) and \(P_2\) as shown in Fig . 6.
(2) Deflection \(y_2\) of the spindle axis due to compliance of spindle support as shown in Fig . 7.

\[
y_1 = \frac{1}{3EI} \left[ P_1 q^2 (l + q) - 0.5P_2 opq (l - o / l) - M_r q \right]
\]
(18)
\(y_2 = \frac{P_2 a - M_r + P_1 (l + q)}{4K_B} (l + q) + \frac{P_2 p + M_r - P_1 q}{4K_A} \frac{q}{l}
\]
(21)
Where,
\(K_A\) and \(K_B\) are stiffness at support A and B.
The total deflection of the spindle, \( y_t = y_1 + y_2 \) (22)

Table 1. Design Specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
<th>Portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Stainless steel</td>
<td>Shaft</td>
</tr>
<tr>
<td>Power</td>
<td>5kW</td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>1500rpm</td>
<td></td>
</tr>
<tr>
<td>Cutting force ( P_z )</td>
<td>11402.126 N</td>
<td></td>
</tr>
<tr>
<td>Cutting force ( P_y )</td>
<td>2985.324N</td>
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<tr>
<td>Cutting force ( P_x )</td>
<td>5240.35 N</td>
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</tr>
<tr>
<td>Chuck weight</td>
<td>265.56N</td>
<td></td>
</tr>
<tr>
<td>Workpiece weight</td>
<td>3610N</td>
<td></td>
</tr>
<tr>
<td>Material of pinion</td>
<td>Cast iron</td>
<td>Spur</td>
</tr>
<tr>
<td>Material of gear</td>
<td>Cast iron</td>
<td></td>
</tr>
<tr>
<td>Speed of pinion</td>
<td>1500 rpm</td>
<td></td>
</tr>
<tr>
<td>Diameter of pinion</td>
<td>155 mm</td>
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<tr>
<td>Allowable stress</td>
<td>55 MN/m²</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>5kW</td>
<td></td>
</tr>
<tr>
<td>Pressure angle</td>
<td>20 deg, stub</td>
<td></td>
</tr>
<tr>
<td>Velocity ratio</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Material ( T_c = T_e )</td>
<td>AISI cold-drawn steel</td>
<td>Key</td>
</tr>
<tr>
<td>B</td>
<td>31.833x10³N/mm²</td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>20 mm</td>
<td></td>
</tr>
<tr>
<td>Sₜ</td>
<td>10 mm</td>
<td></td>
</tr>
<tr>
<td>F:S</td>
<td>351.633MPa</td>
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</tr>
<tr>
<td>Left bearing of the shaft</td>
<td>Tapered roller bearing</td>
<td>Bearing</td>
</tr>
<tr>
<td>Speed</td>
<td>1500rpm</td>
<td></td>
</tr>
<tr>
<td>Axial load ( F_a )</td>
<td>5240.35 N</td>
<td></td>
</tr>
<tr>
<td>Radial load ( F_r )</td>
<td>1411.516N</td>
<td></td>
</tr>
<tr>
<td>Life</td>
<td>30000hr</td>
<td></td>
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<tr>
<td>Loading ratio</td>
<td>10.601</td>
<td></td>
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<tr>
<td>Right bearing of the shaft</td>
<td>Tapered roller bearing</td>
<td></td>
</tr>
<tr>
<td>Type of bearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radial load ( F_r )</td>
<td>13265.589N</td>
<td></td>
</tr>
</tbody>
</table>

| Bending force \( P_1 \) | 11436.826N          | Deflection |
| Bending force \( P_2 \) | 437.114N            |           |
| Distance, \( o \)       | 90mm                |           |
| Distance, \( p \)       | 775mm               |           |
| Distance, \( q \)       | 135mm               |           |
| Distance, \( l \)       | 865mm               |           |
| Reactive moment \( M_r \) | 540.390x10³N/mm² |         |
| Modulus of elasticity \( E \) | 206.01x10⁶N/mm²² |         |
| Moment of inertia \( I \) | 2.040x10⁶mm⁴     |         |
| Stiffness, \( K_A \)    | 3000kg/mm           |         |
| Stiffness, \( K_B \)    | 4000kg/mm           |         |

Table 8. Results Data

<table>
<thead>
<tr>
<th>Item</th>
<th>Data</th>
<th>Portion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Number</td>
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<td>Bearing</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>80mm</td>
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</tr>
<tr>
<td>Outer diameter</td>
<td>140mm</td>
<td></td>
</tr>
<tr>
<td>Right bearing of the shaft</td>
<td>30220</td>
<td></td>
</tr>
<tr>
<td>Inner diameter</td>
<td>100mm</td>
<td></td>
</tr>
<tr>
<td>Outer diameter</td>
<td>180mm</td>
<td></td>
</tr>
<tr>
<td>Module</td>
<td>5 mm</td>
<td>Spur</td>
</tr>
<tr>
<td>Face width</td>
<td>63 mm</td>
<td></td>
</tr>
<tr>
<td>Dynamic force</td>
<td>5751.628 N</td>
<td></td>
</tr>
<tr>
<td>Wear force</td>
<td>25512.820N</td>
<td></td>
</tr>
<tr>
<td>Endurance force</td>
<td>7565.505 N</td>
<td></td>
</tr>
<tr>
<td>( y_1 )</td>
<td>0.133mm</td>
<td></td>
</tr>
<tr>
<td>( y_2 )</td>
<td>0.367mm</td>
<td></td>
</tr>
<tr>
<td>( y_t )</td>
<td>0.480mm</td>
<td></td>
</tr>
</tbody>
</table>

VI. CONCLUSION

The design of Spindle assembly for CNC lathe machine was fabricated by using Fagor CNC lathe machine. Design of machine plants is concentrated on cutting for aluminium and stainless steel, because only 5kW load and available stepper motor can drive. The dimension of workpiece to be operated on designed CNC lathe machine are 200mm in diameter and 1500mm in length. Spindle assembly contains shaft, gear, bearing, key and chuck. All design calculations are dependent on shaft design. Shaft is hollow shaft and made of stainless steel. In spur gear design, pinion and gear are made with cast iron. Taper roller bearings are used in this system and give high rotating accuracy. In Key design, rectangular key is used. Key is made with AISI cold-drawn steel.
REFERENCES


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