Lower Speed Stability Analysis of Large Hybrid Differential Turntable

QINGHUA YU, SHUJIANG CHEN, CHANGHU LU and JINKUI MA

ABSTRACT

There are some differences between the existence of kinetic friction and static friction when the static pressure turntable starts. This may lead to large rotary table come into the crawling problem and poor movement at lower speed. This paper investigates a new type of differential turntable with dynamic and static pressure. The Reynolds equation of logarithmic spiral groove is deduced. Through the establishment of the turntable motion model, using the flow equilibrium, the turntable movement statuses with different working conditions are discussed by Matlab. The conclusion shows that the hybrid differential table eliminates the crawling phenomena, and makes the turntable run steadily.

INTRODUCTION

Turntable aims to make the workpiece fixed and supported, and follows the instructions from the controller to drive the workpiece rotational. The current large turntable mainly adopts a traditional way of pure hydrostatic lubrication. The shortcomings of the hydrostatic lubrication are that the equipment demand of oil supply system is higher, power loss is bigger especially at higher speed. And

---

1 Qinghua Yu, Shujiang Chen, Changhu Lu, Jinkui Ma. School of Mechanical Engineering, Shandong University, Jinan, 250061. The project was supported by the National Natural Science Foundation of China (51575318) and the Fundamental Research Funds of Shandong University (2014YQ017).
the most important problem is that it cannot eliminate the difference between dynamic friction and static friction at startup. So the upper turntable at lower speed is easy to come into "crawl state". Crawl will reduce the turntable positioning accuracy; affect the surface machining quality heavily. It even leads to processed parts become scrapped and causes the turntable to wear out faster.

Lower speed performance is one of the most important symbols of the turntable. Stability of lower speed movement is the focus and direction of study [1]. A major factor of the turntable lower speed stability is the influence of friction torque [2]. To better improve the performance in lower speed, this paper puts forward a new type of differential turntable. The static pressure oil supply system starts for the rotary table at first. Then start the central table. With the increase of rotational speed, dynamic pressure does effect. At the same time dynamic pressure and static pressure bear all the load on the turntable. The hybrid differential turntable uses the advantages of hydrostatic lubrication and dynamic pressure lubrication [3], and it can also avoid their shortcomings. Due to the high-speed rotation of central table, the upper table starts in the condition of kinetic friction. After spindle rotating normally, dynamic pressure effect of oil wedge increases the load capacity of the turntable. Differential rotary table through the "differential" movement maintain large velocity difference between the central table and upper table, and form the dynamic pressure of oil film. It can eliminate the difference between the dynamic and static friction. This prevents the emergence of the crawling problem and guarantees the stability of the turntable in lower speed. This study will open up a new way of improving the indexing precision and the positioning accuracy of large precise turntable.

This paper is based on the motion analysis of turntable. Using Reynolds equation and flow equilibrium, through the establishment of mathematic model, the phenomenon of crawl state is discussed [4]. The working status of the upper table is also analyzed with the dynamic pressure and static pressure joint working condition. This case shows that the system eliminates the difference between the kinetic and static friction torque when turntable starts and the impact on the turntable running smoothness.

![Figure 1. Structure of turntable.](image-url)
1 TURNTABLE STRUCTURE

The hybrid differential turntable structure is shown in Figure 1. It is made up of three parts: upper table, central table and the base. The oil film between the central table and the base is pure hydrostatic lubrication. The oil film between the central table and the upper table is hybrid lubrication. Differential turntable is the combination of dynamic and static pressure lubrication.

The motor drives the driving wheel synchronously rotate. Driving wheel makes driven wheel rotate through the belt. The upper table and the driven wheel are linked on the same axis, and turn synchronously.

The structure of the upper surface of central table is shown in Figure 2. The inside of the fan oil cavity is static pressure oil cavity. The lateral spiral oil cavity is dynamic pressure oil cavity. If the dynamic pressure oil cavity doesn't move, the central table will turn into hydrostatic lubrication.

![Figure 2. Structure of the upper surface of central table.](image)

2 TURNTABLE MOTION MODEL

The synchronous belt is completely elastic deformation. Belt tensile elasticity can be expressed as:

\[
F = \frac{ES\Delta L}{L}
\]

(1)

Where \( E \) is the belt elastic modulus, \( S \) is the cross-sectional area, \( \Delta L \) is the deformation, and \( L \) is the belt length. From the pulley of belt tension, driven wheel angular acceleration can be expressed as:

\[
J\ddot{\delta} = M_{belt} - 2cr'\Delta v - M
\]

(2)
Where \( J \) is the rotational inertia of the driven wheel and the upper table, \( c \) is the damping coefficient, \( r' \) is the radius of the driving wheel, and \( M \) is the friction torque on the rotary table. Using Euler method, the upper table rotating angular velocity and angular displacement can be expressed as:

\[
\Delta \delta (t + \Delta t) = \Delta \delta (t) + \Delta \delta (t) \Delta t
\]

\( (3) \)

\[
\Delta \delta (t + \Delta t) = \Delta \delta (t) + \Delta \delta (t + \Delta t) \Delta t
\]

\( (4) \)

3 REYNOLDS EQUATION

The oil film pressure in the upper and central table is controlled by Reynolds equation. The logarithmic spiral area can be shifted into a fan shaped area based on the coordinate transformation. So the non-dimensional Reynolds equation \([5]\) can be formulated as:

\[
\frac{\partial}{\partial \xi} \left( \frac{h \xi}{h \eta} \frac{\partial p}{\partial \xi} \right) + (1 + \frac{1}{\cot \beta}) \frac{1}{\xi} \frac{\partial}{\partial \eta} \left( \frac{h \eta}{h \xi} \frac{\partial p}{\partial \eta} \right) - \left( \frac{1}{\cot \beta} \right) \left[ \frac{\partial}{\partial \eta} \left( h \xi \frac{\partial p}{\partial \xi} \right) + \frac{\partial}{\partial \xi} \left( h \eta \frac{\partial p}{\partial \eta} \right) \right] = 6 \frac{\partial h}{\partial \eta} + 12 \frac{\partial h}{\partial \tau}
\]

\( (5) \)

4 SIMULATION ANALYSIS

4.1 Static Pressure Work Alone

The friction coefficient range of lubrication is 0.001 ~ 0.01. This paper assumes that the static friction force coefficient is 0.01, and the kinetic friction coefficient is 0.001. Static pressure friction torque can be expressed as:

\[
M = \frac{2}{3} \mu' Wr
\]

\( (6) \)

Where \( \mu' \) is the coefficient of friction, \( W \) is the hydrostatic capacity, and \( r \) is the radius of hydrostatic capacity.
### TABLE I. BEARING AND BELT PARAMETERS.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>outer radius of the spiral groove oil chamber</td>
<td>mm</td>
<td>435</td>
</tr>
<tr>
<td>sealing edge radius of spiral groove oil cavity</td>
<td>mm</td>
<td>425</td>
</tr>
<tr>
<td>inner radius of the spiral groove oil chamber</td>
<td>mm</td>
<td>335</td>
</tr>
<tr>
<td>spiral groove oil cavity groove width ratio</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>spiral groove oil cavity groove depth</td>
<td>μm</td>
<td>125</td>
</tr>
<tr>
<td>spiral angle of the spiral groove oil chamber</td>
<td></td>
<td>(\pi / 4)</td>
</tr>
<tr>
<td>the length of the parallel plate</td>
<td>mm</td>
<td>75</td>
</tr>
<tr>
<td>the width of the parallel plate</td>
<td>mm</td>
<td>35</td>
</tr>
<tr>
<td>outer radius of the static pressure oil cavity</td>
<td>mm</td>
<td>325</td>
</tr>
<tr>
<td>outer sealing edge radius of static pressure oil cavity</td>
<td>mm</td>
<td>300</td>
</tr>
<tr>
<td>inner sealing edge radius of static pressure oil cavity</td>
<td>mm</td>
<td>225</td>
</tr>
<tr>
<td>inner radius of the static pressure oil cavity</td>
<td>mm</td>
<td>195</td>
</tr>
<tr>
<td>modulus of elasticity</td>
<td>kgf / cm(^2)</td>
<td>5500</td>
</tr>
<tr>
<td>cross-sectional area</td>
<td>mm(^2)</td>
<td>476</td>
</tr>
<tr>
<td>quality of the upper table</td>
<td>kg</td>
<td>3620</td>
</tr>
</tbody>
</table>

![Figure 3. Motion state: (a) the angular displacement, (b) the rotary speed.](image)

According to the parameters and the equations of motion, assuming that the motor runs at a constant rotational speed of \(10r/min\) and the transmission ratio is 10, the motion state of upper table can be got in Figure 3. The upper table doesn't move in the static friction force at the beginning. When the belt deformation gradually increases, elastic force exceeds the maximum static friction force, the relative stationary state between the friction pairs is broken. The friction
transforms from static friction to kinetic friction. Then the upper table will produce an instantaneous acceleration. When the upper table's speed is higher than the speed of the driving wheel, belt deformation will reduce, friction force will change back to static friction force. So the crawling phenomenon appears.

4.2 Dynamic Pressure and Static Pressure Work Together

The total friction torque is the sum of the dynamic pressure friction torque and the static friction torque. If the work conditions are as below: oil supply pressure is 1MPa, rotational speed of central table is 200r/min, the motor speed is \(10 \text{r/min}\), the transmission ratio is 10. Then the motion state of upper table could be got, as shown in Figure 4.

After the central table runs, the dynamic pressure effect between upper and central table is obvious. Compared with the pure static pressure work alone, the friction torque increases. The rotary motion levels off after shocks. However, after eliminating the influence of the crawl, the system runs more smoothly.

Figure 4. Motion state: (a) the angular displacement, (b) the rotary speed.

5 CONCLUSION

When the hydrostatic lubrication runs alone at lower speed, due to the differences of the friction coefficients between conditions of moving and stopping, the crawling phenomenon appears. When the central table rotates at higher speed, even the upper table runs at lower speed, the relative speed between the upper table and the central table is also higher, so it eliminates the difference of static friction and kinetic friction. As a result, the crawling phenomenon is eliminated. This novel design greatly improves the stability of turntable in lower speed.
REFERENCES


