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Optimization Design and Analysis of Rotary Indexing Mechanism of Tool Magazine in Machining Center

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Abstract

In order to achieve a faster rotation speed and lower impact load of the machining center armless type tool magazine during the rotary indexing process, the rotation and positioning characteristics of the rotary indexing mechanism were studied. The structural design of the Geneva mechanism used to drive the tool magazine was completed, and the optimized design scheme of the new double-pins without the locking arc Geneva mechanism to replace the single-pin locking arc Geneva mechanism was finally determined. The tTwo schemes were modeled and compared by kinematics based on NX and ADAMS. The results of kinematics contrast simulation show that the double-pins Geneva mechanism structure without locking arc has the advantages of being faster in rotational speed, smaller in impact load and more stable running condition, so that the speed of machine tool change while greatly reducing device wear and improve the durability of the device.

Keywords: Geneva mechanism, optimization design, tool magazine, machining center.

1. Introduction

CNC machining center is the mainstream and popular equipment of the current manufacturing industry [1, 2]. Its biggest feature is the tool storage and automatic tool change function, which is mainly realized by the tool magazine and automatic tool changer [3, 4]. At present, the operating efficiency and reliability of the tool magazine components have become an important factor restricting the operation efficiency and reliability of CNC machine tools. Although domestic and international research has been done to improve the tool change speed and tool change stability [5-12], but there is still a lot of improvement. Therefore, it is necessary to study the rotation and positioning characteristics of the tool magazine drive mechanism to achieve a faster rotation speed and a lower impact load during the tool change process.

In this study, the 16T armless type rotary indexing mechanism was taken as the research object. Firstly, the initial scheme of the rotary indexing mechanism was designed. Then, through the optimization design calculation of the mechanism, the final rotary indexing mechanism was determined to be a double-pin without locking arc, which is a brand-new tool magazine drive mechanism, which increases the rotation speed while reducing the impact load, reduces the tool magazine wear, and improves the tool magazine durability. Based on NX and ADAMS software, the 3D modeling and kinematics comparison analysis of the pre-optimized and optimized mechanisms were carried out, and the rotation and positioning characteristics of the mechanism were obtained. From the comparison of the kinematics simulation results, the rotational speed of the optimized structure was doubled compared with the old structure, and the impact load was greatly reduced~~,~~ Consequently, the wear of the tool magazine was reduced, and the durability of the tool magazine was improved.

2. Methodology of design and optimization for rotary indexing mechanism

2.1. Analysis of tool change process in tool magazine

The main part of the armless type tool magazine is mainly composed of the base body, the connecting seat, the sliding rail, the indexing plate, the tool magazine plate and the driver plate pins. The main part of the armless type tool magazine is shown in Figure 1.

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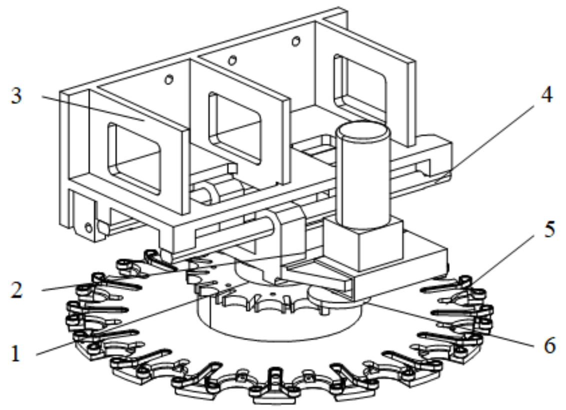


1. Indexing plate 2. Connecting seat 3. Base body

4. Sliding rail 5. Tool magazine plate 6. Driver plate & pin

Figure 1: Armless type tool magazine main part structure diagram

The following is a simple analysis of the tool change action of the armless type tool magazine.

1. The spindle moves to the tool change position;
2. The spindle is stopped;
3. The tool magazine moves to the tool change position (grabbing the old tool);
4. The spindle releases the old tool;
5. The spindle moves upwards (let the tool magazine rotate the positioning space);
6. The tool magazine is rotated and positioned to the new tool position;
7. The spindle moves downward (moving to the tool change position);
8. The spindle grasps the new tool;
9. The tool magazine is retracted to the initial position (end tool change).

During this entire tool change process, the forward and backward movement of the tool magazine is completed by the cylinder drive. This action can already achieve a faster speed. Therefore, the efficiency of the entire tool change process is mainly determined by the speed of the indexing plate rotation and positioning. It is necessary to select a more suitable rotational positioning scheme to increase the indexing plate rotation speed while ensuring a smooth rotation process and to reduce impact during positioning and startup

2.2. Determination of the rotary indexing mechanism

The rotary indexing mechanism is mainly used to realize the indexing and turning motion of the tool magazine, so it is very important to ensure the speed and reliability of the tool magazine. At present, most of the armless type tool magazines use the single-head double-lead worm gear mechanism, the double-lead cylindrical cam mechanism and the Geneva mechanism to realize the rotary indexing of the tool magazine. Among them, the single-head double-lead worm gear mechanism can adjust the transmission gap of the worm and worm at any time to achieve accurate indexing index, but the structure of the transmission mechanism is complicated and difficult to process. The double-lead cylindrical cam mechanism has strong bearing capacity and stable indexing, and is suitable for a mechanism with a large load, but at the same time, its disadvantage is that the structure is complicated and the processing cost is high [13]. The Geneva mechanism has high rotational efficiency, small impact load, stable operation, simple structure and easy manufacture [14]. Therefore, the rotary indexing mechanism of the tool magazine is realized by the Geneva mechanism.

The Geneva mechanism is a mechanism that can convert the continuous rotation of the active part into a periodic intermittent motion of the driven part, and is commonly used in various rotary indexing mechanisms. The Geneva mechanism can be classified into external meshing, internal meshing and spherical Geneva mechanism according to different meshing modes. The armless type tool magazine adopts an external meshing Geneva mechanism to realize the rotary indexing action. The active part of the external meshing Geneva mechanism is the driver plate and the pin, and the driven part is the indexing plate. The working principle is as follows: the active part performs a continuous rotary motion at a constant angular velocity, and the driven part performs a periodic intermittent rotary motion. When the pin does not enter the indexing plate, the locking limit action is completed by the concave locking arc of the indexing plate and the convex locking arc of the driver plate. After the pin enters the indexing plate, the lock arc is released and the driver plate drives the indexing plate to rotate. In this way, a one-way intermittent rotational motion is outputted in a loop.

2.3. Calculation of the parameters of the Geneva mechanism

Different slot number can result in different angular velocity and angular acceleration changes: the less the slot, the greater the change in angular acceleration and the greater the impact and wear. Therefore, the number of slots of the external meshing Geneva mechanism for the tool magazine should not be less than 8. The known research object is a 16T armless type tool magazine, so the number of slots is set to 16. According to the working requirements of the tool magazine, the number of driver plate pin is initially selected as 1.

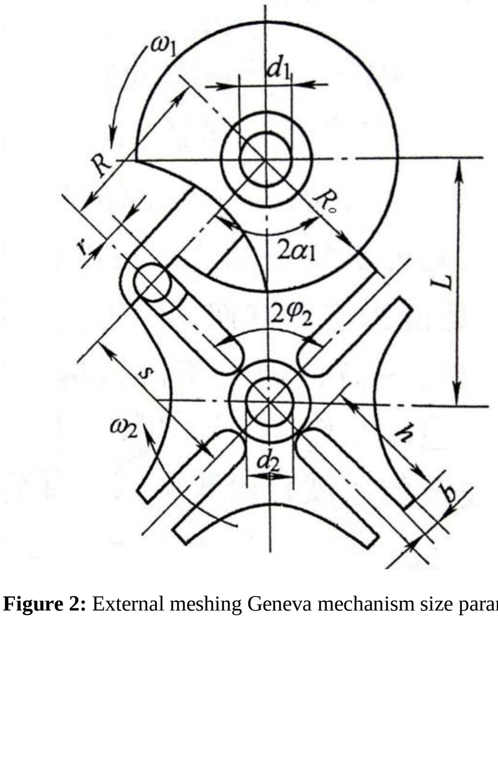


Figure 2: External meshing Geneva mechanism size parameter

The size parameters of the external meshing Geneva mechanism are shown in Figure 2. Specific values can be obtained by the following design calculations:

Center distance: The value of the center distance is determined by the size of the machine space and the form of the tool magazine structure. The larger center distance makes the indexing plate indexing process more stable, but at the same time, the quality of the indexing plate is increased, and the motor driving power is synchronously improved. The smaller center distance can cause the impact at the meshing of the mechanism to become larger. Taking into account the above factors, the value is determined as: $L = 150mm$

Indexing plate movement angle: $2\varphi_2 = 2\pi / \mathrm{Z} = 22.5^\circ$ (1)

Driver plate movement angle: $2\alpha_1 = \pi - 2\varphi_2 = 157.5^\circ$ (2)

Pin center track radius: $R = L \times \sin\varphi_2 \approx 30mm$ (3)

Pin radius: $r \geq R/6 = 5mm$ (4)

Slot top radius: $s = \sqrt{r^2 + (L\cos\varphi_2)^2} \approx 147mm$ (5)

Slot top sidewall thickness: $b = 3 \sim 5mm$ (7)

Slot depth:

$$h = [s - (L - R - r)] + (3 \sim 5mm) = 35mm \quad (8)$$

Radius of locking arc: $R_0 = R - r - b = 20mm$ (9)

Motion coefficient: $\tau = 2\alpha_1/2\pi = (\mathrm{Z} - 2)/2Z = 0.4372$ (10)

The geometric parameters of the Geneva mechanism are listed in Table 1:

Table 1: Geneva mechanism geometric parameters

Parameters	Value
Number of slots/Z	16
Number of pins/n	1
Center distance/L	150 mm
Indexing plate movement angle/$2\varphi_2$	22.5°
Driver plate movement angle/$2\alpha_1$	157.5°
Pin center track radius/R	30 mm
Pin radius/r	5 mm
Slot top radius/s	147 mm
Slot top sidewall thickness/b	5 mm
Slot depth/h	35 mm
Motion coefficient/τ	0.4372
Locking arc radius/R_0	20 mm

2.4. Parametric modeling of Geneva mechanism based on NX

NX is an interactive CAD/CAE/CAM software system that is powerful enough to easily construct a variety of complex parametric entities and models, as well as kinematics and dynamics simulation of related models [15]. It has been widely used by multidisciplinary researchers.

The modelling dimensions of the Geneva mechanism are determined by the above parameters, the 2D drawing is drawn first, and the 3D model is finally completed by NX. The 3D model of the Geneva mechanism is shown in Figure 3.

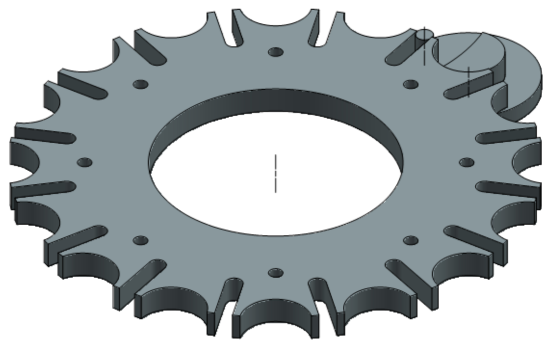


Figure 3: 3D model of Geneva mechanism

2.5. Optimization design of the Geneva mechanism

In order to achieve a higher rotational speed and stability of the tool magazine, the Geneva mechanism is optimized by the following two steps.

2.5.1. Increase rotation speed

It is known that the number of the driver plate pins of the Geneva mechanism is 1 (n = 1), and the number of slots is 16 (Z = 16), that is, the driver plate is rotated for one week, and the indexing plate is rotated by 22.5 degrees, thereby realizing the rotary indexing operation of the tool magazine. At the same time, when n = 1, its motion coefficient $\tau = 0.4372 < 0.5$, that is, the indexing plate movement time is less than the stop time, and the motion efficiency is low. In order to increase the rotational speed of the indexing plate and increase the coefficient of motion without increasing the rotational speed of the driver plate, it is necessary to increase the number of pins of the driver plate.

When the number of slots of the external meshing Geneva mechanism is greater than or equal to 6, the number of pins cannot be greater than 2, so the numbers of pins are 2 (n = 2). In this way, without increasing the driver plate rotation speed, the rotation speed of the indexing plate is doubled, the motion coefficient is also doubled, and the movement time is greater than the stop time.

However, the increase in the number of pins of the Geneva mechanism causes the central angle of the locking arc to become smaller, and its value is calculated by the following formula (11):

$$\gamma = 2\pi / \mathrm{n} - 2\alpha_1 = 180^\circ - 157.5^\circ = 22.5^\circ \quad (11)$$

In the formula (11): n is the number of pin, and $2\alpha_1$ is the driver plate movement angle.

Figure 4 is a comparison diagram of the structure of the Geneva mechanism in the case where the number of round pins is equal to 1 (Figure 4a) and equal to 2 (Figure 4b). The double pins in Figure 4b double the rotational speed, but because there is still a locking arc in the structure, it still needs to complete the typical intermittent movement. During the positioning process, a large impact load is generated when the pin enters the slot every time, and it can be seen from the figure that the locking arc of the double-pins mechanism becomes very small only 22.5 degrees. This results in a locking arc that is prone to wear and its durability is greatly reduced. Therefore, it is necessary to further optimize the design.

2.5.2. Improve stability

In order to improve the stability of the rotary indexing movement of the tool magazine, we have determined the following improvement requirements: avoiding the rigid impact during the operation of the mechanism and reducing the wear during the operation of the mechanism to obtain a precise positioning position. According to the above design requirements, the double pins structure is still adopted, and the parameters, such as the center distance, the indexing plate movement angle, the driver plate movement angle, the pin center track radius, the pin radius, and the slot depth are unchanged. An optimized double-pins Geneva mechanism without locking arc was redesigned as shown in Figure 5 below.

As can be seen from the above Figure 5, the optimized slot top radius (s1) is larger than the initial slot top radius (s). It can be seen from the above Figure 5 that the value of s1 is calculated by the formula (12):

$$s1 = \sqrt{L^2 + (R - r)^2} \approx 152mm \tag{12}$$

In the formula (12): L is the center distance, R is the pin center track radius, and r is the pin radius.

It can be seen from Figure 5 that a transitional arc is newly designed between the initial slot top circle and the optimized slot top circle. When the pin 1 is disengaged from the slot along the transitional arc, the pin 2 just enters the transitional arc of the slot. The transitional arc acts as a lock and positioning. At the moment of Figure 4, the Geneva mechanism is in a stationary state. When the Geneva mechanism is in this state, the line between the centers of the two pins and the line between the center of the indexing plate and the center of the driver plate are perpendicular to each other, that is, the instantaneous angular velocity of the rotation of the indexing plate is 0 (ω = 0), thereby avoiding the rigidity of the mechanism. At the same time, the optimization mechanism cancels the original small locking arc design, which reduces the wear during operation and improves the durability of the mechanism, thus achieving the optimal design requirements.

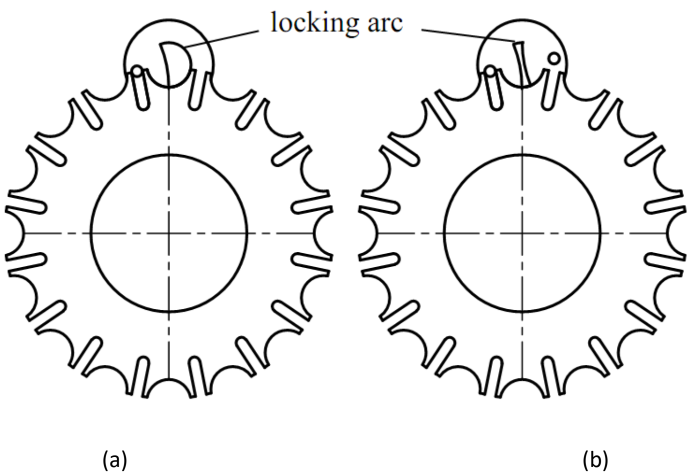


Figure 4: Different number of pins comparison chart

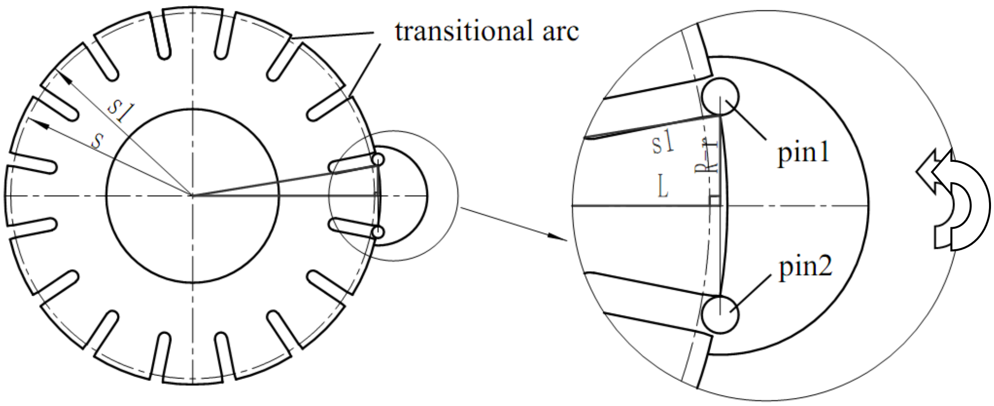
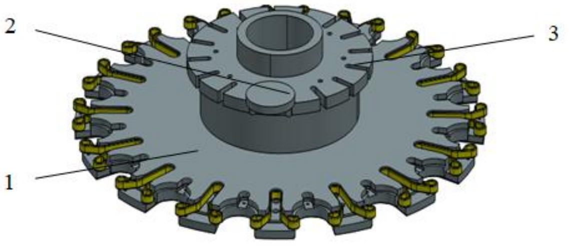


Figure 5: Optimized Geneva mechanism 2D drawing

3. Comparative analysis of kinematics for rotary indexing mechanism

3.1. Parametric modeling of rotary indexing mechanism based on NX

The optimized Geneva mechanism model and other parts models of the tool magazine are built in NX 3D modeling software. These parts are assembled together as required, and finally assembly model of the rotary indexing mechanism of the tool magazine as shown in Figure 6.



1. Tool magazine plate 2. Driver plate & pin 3. Indexing plate

Figure 6: Assembly model of rotary indexing mechanism

3.2. Comparative analysis of mechanism kinematics based on ADAMS

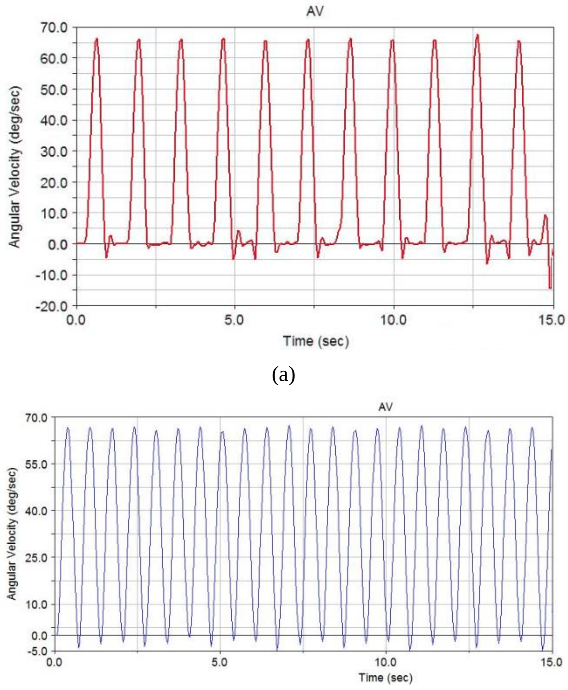
In order to verify the optimization effect of the new Geneva mechanism, the ADAMS software was used to compare the kinematics of the old and new Geneva mechanisms.

The first step is to simplify the tool magazine assembly model in the NX software, remove excess parts, and finally retain only the necessary components such as indexing plate, driver plate and pins. Export the Parasolid format (.x_t format file) and import it into the ADAMS software. Set the unit to MMKS, add the gravitational acceleration and material properties, and finally complete the pre-processing.

The second step is to constrain the indexing plate and the ground through the revolute joint in the ADAMS software. The driver plate and the ground are constrained by the revolute joint. The pin and the driver plate are constrained by the revolute joint. The driver plate and the indexing plate, the pin and the indexing plate are constrained by the contact joint. The specific parameters of the contact joint are set as follows: the stiffness is 10e6, the force exponent is 1.5, the damping is 10, the penetration depth is 0.01, and the static friction factor is 0.1, the dynamic friction factor is 0.08. A rotational drive with a rotational speed of 45r/min was applied to the driver plate, and finally the simulation model was constructed.

4. Results and discussion

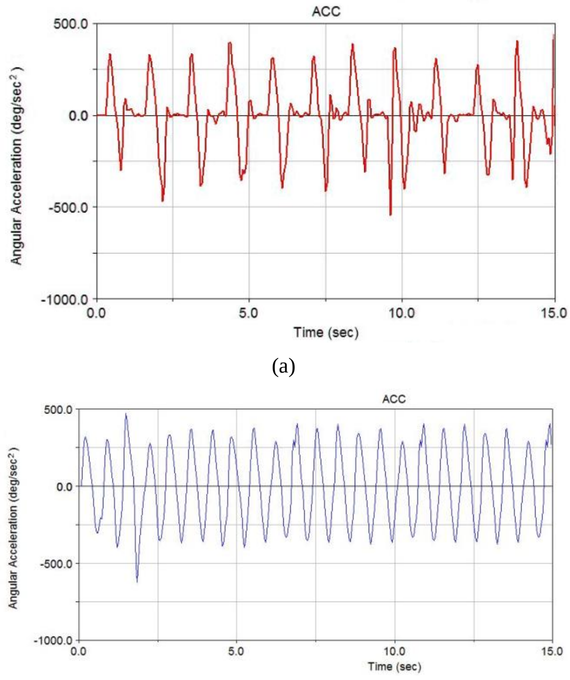
The new and old simulation models are submitted to the solution, and the angular velocity and angular acceleration curves of the indexing plates in the old and new mechanisms are plotted in the post-processing section. The results are shown in Figure 7 and Figure 8.



(a)

(b)

Figure 7: AV-Curve comparison chart of old & new mechanisms



(a)

(b)

Figure 8: ACC-Curve comparison chart of old & new mechanisms

In Figure 7, the red curve is the angular velocity curve of the old mechanism indexing plate in [16], and the blue curve is the angular velocity curve of the new mechanism indexing plate. In Figure 8, the red curve is the angular acceleration curve of the old mechanism indexing plate in [16], and the blue curve is the angular acceleration curve of the new mechanism indexing plate.

After comprehensively comparing and analyzing the curves of Figure 7 and Figure 8, the following conclusions can be drawn:

1. In the same 10 seconds, when the new mechanism turned 15 indexing stations, the old mechanism only turned 7.5 indexing stations, so the new mechanism's rotation speed doubled.
2. In both the old and the new mechanisms, the angular velocity and angular acceleration of the indexing disc are constantly changing. The angular velocity is maximized when the center of the indexing plate, the driving plate and the pin are collinear. The angular acceleration is exactly zero when the angular velocity is maximum.
3. The old mechanism indexing plate has a period in which the angular velocity is equal to 0 in the cycle, so that an impact phenomenon occurs during acceleration. The angular velocity of the indexing plate of the new mechanism is not in the state of 0 for a long time, and it is not necessary to repeatedly overcome the static inertia, so the impact load is greatly reduced, the wear is reduced and the durability is improved.

In summary, the optimized new Geneva mechanism doubles in rotational speed and is approximately in continuous motion. The reduction in the angular velocity variation causes the mechanism to not repeatedly overcome the static inertia. At the same time, because of the existence of a transition arc, the impact and vibration are also smaller than the old mechanism. These have proven that the optimized new Geneva mechanism can completely replace the old Geneva mechanism.

5. Conclusion

In this study, the rotary indexing mechanism of the tool magazine was designed and optimized. The newly designed double-pins without locking arc Geneva mechanism has been proved by motion simulation to prove that it can completely replace the old single-pin Geneva mechanism with locking arc. At the same time, the simulation analysis results show that the new mechanism rotation speed is doubled and the impact load is greatly reduced, which provides an important reference for subsequent research.

In the next stage, this study will test the movement of the new mechanism under actual conditions to further verify the angular velocity and angular acceleration of the mechanism. The research on the influence of the manufacturing process on the running state of the Geneva mechanism is completed to achieve a more optimized design of the rotary indexing mechanism.

Acknowledgements

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