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The Design, Modeling and Analysis of Slotting Mechanism on Machine Tool with MATLAB

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Abstract. A slotting machine tool is a special equipment in the factory to process the work pieces by cutting head. Nowadays the demand for the machine has become stricter as the endurance and the efficiency have been regarded as the most valuable estimating parameter of whether a slotting machine is consummated or not. In this paper, a design method is put forward to achieve this goal. By disassembling the whole working mechanism into 3 main mechanisms such as the reduction mechanism, the slotting mechanism and the feeding mechanism and discussing the proper and suitable sub-mechanism, the best selection can be carried out. Then by combining the programming language MATLAB with the kinematic analysis of the mechanism itself, the profile of most essential component—the cam mechanism can be drawn to showcase the outline. Using MATLAB can make the analyzing process comprehensible and virtual. Overall, the advantages of this design include the high durability and efficiency, the strong applicability, the interacting bond between the implementation and the MATLAB programming algorithm with high accuracy.

Keywords: slotting machine, MATLAB, mechanism design, kinematic analysis

1. Introduction

In the context of contemporary machinery processing industry, the durability of individual component and the efficiency of the brand product machining procedure are both indispensable and consequential part in slotting mechanism design [1-3]. The former will be quite helpful in cutting down the unnecessary expenditure on frequent maintenance, and it can also assist the latter, which is the primal goal of all machinery designs. Basically, slotting machines can be divided into three parts, the electric motor, the transmission, and the final controlling element [4]. Apparently, the actuator is the decisive session of whether a slotter can be categorized as efficient, so this study will mainly focus on forming an effective kinematic model that can make most parts of the actuator satisfy the function of themselves and meanwhile guarantee the components will have considerable endurance. The model building process also needs to be divided logically and confirming the main structures of the slotter as the reduction gearbox, the slotting mechanism and the feeding mechanism is vital for the accuracy of modelling. After that, the overall research will focus on fulfilling the demand of these 3 aspects of slotting mechanisms to figure out an efficient and durable model.

In this study, we will combine the modeling process with a programming language MATLAB, which is developed to support the direct transformation of equals and picture graphs [5,6]. By

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analyzing the curves and the fluctuation of the statistical line, we can adjust the modeling process to turn the nuance of the graph into positive variations in making the grand slotter more perfect. Through MATLAB [7,8], we intend to identify a reasonable and logical model that can exert the full potential of slotting mechanism [9,10], which sure can bring numerous advantages more than just reducing expenditure.

The study introduces the methodology that combines the modeling process with programing tool, and this offers another dimension of designing mechanical products. For the developers, time can be saved due to the design's simplicity and flexibility on modeling—changing a few parameters or rewriting some equals will generate another applicable alternative, largely enhance and diversify the products' yield and categories. For the entrepreneurs, increase in efficiency of both industrial product-generation procedures and the model developers not only makes considerable benefits but also offer them motivation to invest in further products research, and this serves consumers in lower price, better functionality and higher availability due to iteration in slotting mechanism brought by a more and more comprehensive model and programming process that based on the original model discussed here and later.

In this article, first we will disassemble the three basic parts of slotting mechanism to comprehend their demand, then based on these standards to schedule the functions of different modules in the overall modelling process, and after that we'll discuss the interconnection between these modules to determine the final decision of mode and module selection [11,12].

2. Function analysis and practical application

As introduced, one of the 3 main components of the slotter's structure is the reduction gearbox, and its usage is to maintain the gear ratio at a constant level. For another irreplaceable mechanism, the slotting mechanism, keeping the slotting process steady and promising a quick- return in the slotter's back route are its function. Feeding mechanism also needs to satisfy 2 demands: controls the feed rate at a relatively low level and makes the amount of feed intermittent. To guarantee the study is rigorous and scientific, I suggest not only focusing on the main functions but also to shed light on multiple sub-functions to make the process of slotting more detailed. Beneath the main functions, there are 4 sub-functions, A, the transmission reduction, B, the feed reduction, C, the reciprocating sharp motion and D, the work piece feed motion, respectively. To understand these sub-functions, we need to know how these functions are achieved. For the first two reduction parts A and B, they are realized by 4 transmission methods: the chain drive, the gear drive, the belt drive, and the worm drive. Meanwhile, for the other parts of the sub-functions C and D, their athletic movements are basically the same, both can be driven by 3 mechanisms: the crank-slider mechanism, the cam mechanism, the rotating guide bar mechanism. But the work piece feed motion, D, has another method to fulfill its function, which is achieved through the ball screw assembly. But the final design can't contain all these methods, so choosing one way to reach the goal for each sub-function part is considerably vital. Taking the practical application and the significance to make the whole slotting mechanism efficient and durable for premise, the coordination and the logical inter-connection of each sub-function is the key to reaching the study's goal, so I will interpret that below. For A, the transmission reduction mechanism, taking the reciprocating slotting mechanism and the feeding movements require fine athletic coordination relationship in consideration, choosing an electric motor to supply energy for the system will uncontrovertibly be a wiser decision than placing a separate motor on each component. And after being reduced by gear in velocity, for B, the feed reduction, selecting the V-belt transmission is the best choice. Though using gear transmission has some nonnegligible advantages such as the relatively smooth transmission process and low noise,

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but its transmission route would be too long to make the whole slotting machine cumbersome and over-huge, so despite the gear ratio of the V-belt transmission mechanism maybe slightly higher than the other, taking the light demand of the ideal design of the slotting machine in consideration, adopt the V-belt transmission mechanism still will be the better choice. Next, for C, the reciprocating sharp motion, the rotating guide bar mechanism is the fittest choice. Firstly, utilizing the rotating guide bar mechanism satisfies the demand of quick-return, and secondly, it can stand and transmit relatively great power, also satisfies the grand demand of the slotter's durability. In comparison with this mechanism, the cam mechanism though could guarantee the precise trajectory of the cutter head, the over-complexity of the cam's producing process and the weaker capability of standing power make it relatively unsuitable for application, and that makes the rotating guide bar mechanism a better option. And finally, for D, the work piece feed motion, combining the selection of A, B and C sub-functions, the cam mechanism is appropriate. Again, precise movements drove by the ball screw assembly is undoubtedly beneficial, but the odious environment of the slotting process and the frequent collision will probably make the screw especially fragile, which can lead to the failure of achieving the goal of endurance of the slotting mechanism. Besides, given that the coordination of each part of the mechanism is quite essential, using the cam mechanism to stand the power of the electric motor that has been reduced by the V-belt mechanism is more proper to help feed the motion. In summary, based on the principles of optimal application, and meanwhile considering the practical operating environment and the unique characteristics of the mechanism itself, for A, the transmission reduction mechanism, adopting gear transmission; for B, the feed reduction mechanism, choosing V-belt transmission; for C, the reciprocating sharp mechanism, selecting the rotating guide bar mechanism; and for D, the work piece feeding mechanism, employing the cam mechanism.

3. Kinematic modeling and analysis

Based on the mechanism selection of all the above, now we can model the grand slotting mechanism.

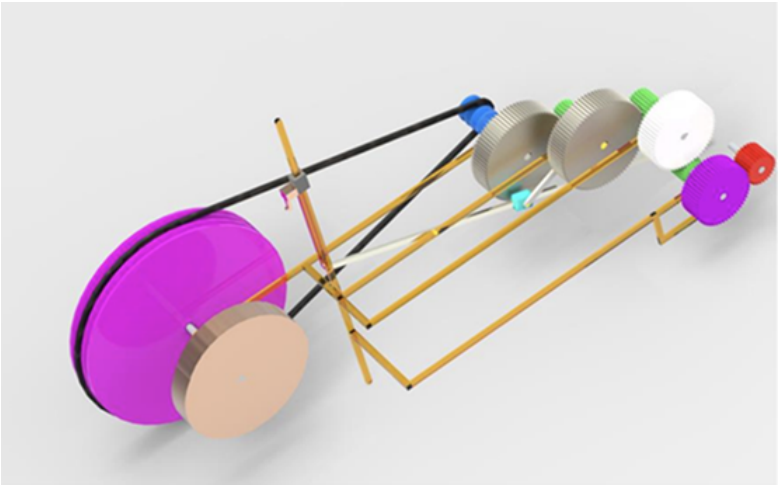


Figure 1. The whole simulation diagram of the moving mechanism 1

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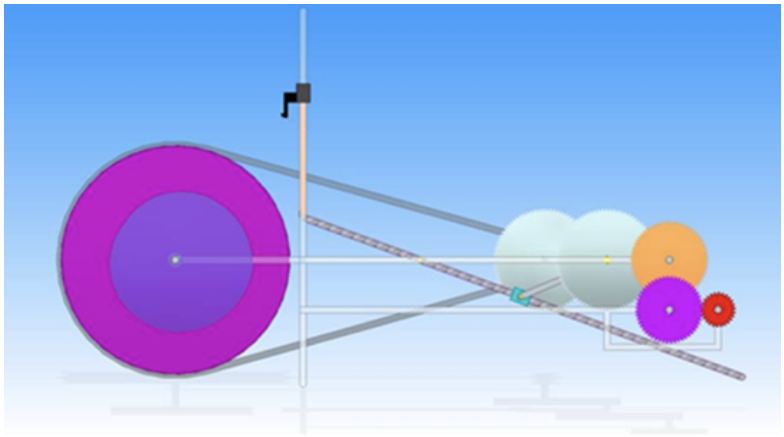


Figure 2. The whole simulation diagram of the moving mechanism 2

As manifested, the whole mechanism is combined with components that can be categorized as 2 types: the bar mechanism and the gear mechanism. The electric motor is set to motivate the smallest red gear to rotate, and the rotation of the red gear drives the purple gear to spin. Then the green gear behind the purple gear is forced to spin, meanwhile the horizonal bar that connected to the purple gear is forced to rotate in a relatively small angle that causes the vertical bar linked to it to move ups and down through the slider that connected to the V- belt that nests on the biggest purple gear which is placed at the bottom of the model' gears. After that, the same event happens on the small sub-mechanism that is on the top of the purple gear which is driven by the orange gear. The next level's situation is slightly different, the white gear that motivated by the second green gear that attached to the orange gear has a connecting rod which is attached to the green slider on a inclined bar tied to the vertical bar, and this design is intend to limit the spinning angle of the white gear to transmit the power generated by the first two gear more thoroughly to guarantee the efficiency of the system. The next level is like the level that has the orange gear, but the horizonal bar of it was connected to the bar that is placed at the center of the biggest purple gear to gain enough maintenance. The function of the thinner purple gear attached to the second white gear is to make sure the power received by the second white gear is conveyed 100 percent to the V-belt system, then the biggest purple gear rotates to motivate the whole slotting mechanism. The overall process can be concluded as through the gears' three-stage reduction, the crank's speed is decreased from 240r/s to 1r/s. Also, the crank (the inclined bar) can satisfy the demand of quick-return and the stability of the mechanism. Lastly, due to the strict cooperation of the work piece feeding mechanism and the slotting mechanism, the period should be limited to 1 second, the first 0.4 second for slotting, the second 0.4 second for work piece feeding, and the 0.1 second in between for safety.

And now we shall explain the design and careful selection of the statistics of the components. First and foremost, the gear reduction mechanism's design is based on the calculation of the gear ratio. The simplified diagram is as follows.

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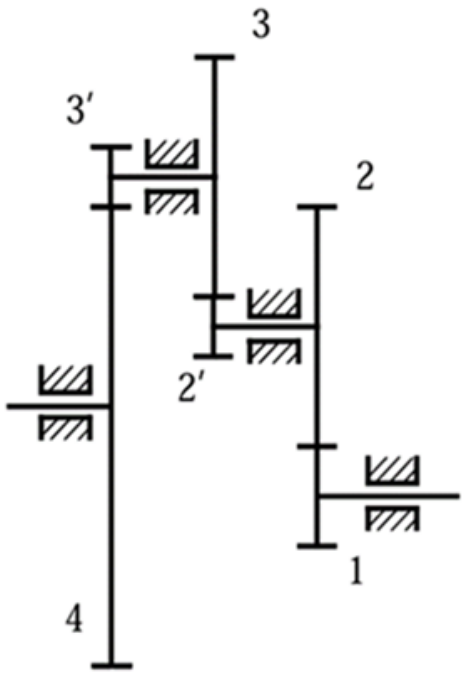


Figure 3. Simplifed diagram of gear mchanism

Through the simplification of the complex kinematic model, it's obvious that the reduction system is a three-stage reduction system as mentioned. And in consideration of the durability and the demand of decreasing the original electric motor drove speed of 1440 r/min to a 60 r/min level, the selection of the gears' parameters is as follows.

Table 1. Gear parameter

Parameter\ Gear	Number of Teeth z	Modul e m	Pitch Diameterd	Face Widthb	Pressure Angle α	Addendum Coefficient h_a*	Clearance Coefficient c*	Center Distancea
Gear 1	26	1mm	26mm	20mm	20°	1	0.25	39mm
Gear 2	52	1mm	52mm	20mm	20°	1	0.25	
Gear 2'	20	1mm	20mm	20mm	20°	1	0.25	40mm
Gear 3	60	1mm	60mm	20mm	20°	1	0.25	
Gear 3'	20	1mm	20mm	20mm	20°	1	0.25	50mm
Gear 4	80	1mm	80mm	20mm	20°	1	0.25	

Compared to the triple reduction gear mechanism, the V-belt mechanism is undoubtedly simpler. To transmit the relatively high velocity of the gears' system to a lower rotation speed on the cam, we select their parameters as follows.

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Table 2. Gear parameter

Parameter\ Gear	Number of Teeth z	Module m	Pitch Diameter d	Face Width b	Pressure Angle α	Addendum Coefficient h_a*	Clearance Coefficient c*
Gear 4'	20	1mm	20mm	20mm	20°	1	0.25
Gear 5	80	1mm	80mm	20mm	20°	1	0.25

Through this two-stage reduction mechanism, the speed of the cam is decreased to 1/36 r/s, perfectly matching the standard.

Besides these 2 mechanisms, another essential mechanism is the oscillating guide bar mechanism. The graph of it is as follows.

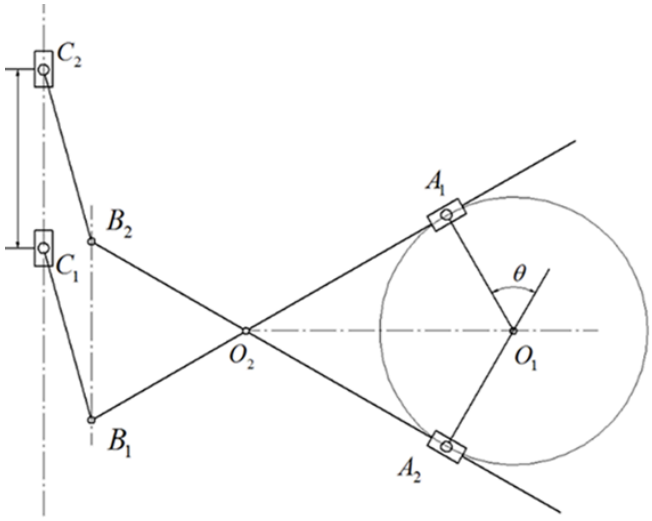


Figure 4. Simplified diagram of swing guide mechanism

To make the explanation of the mechanism clear and comprehensible, we want to note the terms performed on the graph. C1 and C2 stand for the lower tool limit and the upper tool limit, A1, A2 and B1, B2 stand for the different position of the slider and the joint. Given that the advance-to-return ratio K is 2, based on the equal of it can calculate the angle:

$$K = 180 + \theta / 180 - \theta = 2 \tag{1}$$

Obtain that is 60 degrees. When the crank and the guide bar are perpendicular, the slider(tool) is at limit positions, and the angle between them is . According to geometric knowledge, triangle O2B1B2 is equilateral triangle, and the quadrilateral C1C2B2B1 is parallelogram. So BO2 and BC are equal. And to satisfy the force transmission performance requirement, the pressure angle should be as small as possible to determine the distance between the guide bar and O2. That distance is 93.58mm if the pressure angle is only 4 degrees.

At the last part of the kinematic analysis of the mechanism's performance, we will focus on the Whitworth Mechanism. To calculate the mechanism's performance in a mathematical way, we will introduce vector calculations in the analyzing process. The schematic of the vector is as follows.

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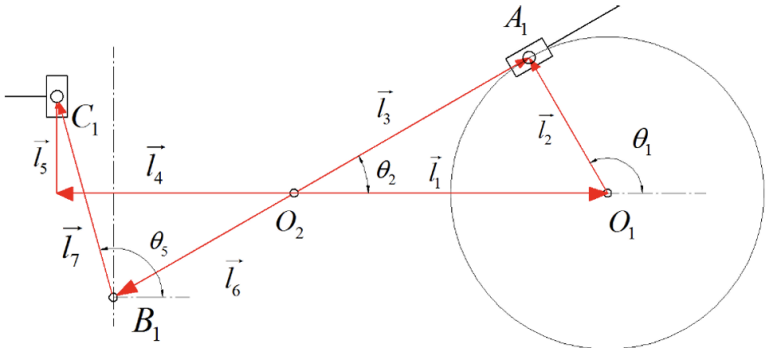


Figure 5. The schematic of the vector

It is obvious that vector L1 plus vector L2 equals to vector L3, and through the calculation of trigonometric functions, we can gain that L1 plus L2cos1 equals to L3cos2, and L2sin1 equals to L3sin2. Combining these two equals together, though taking the square root after moving all the other variables to the other side of the equal, we can gain the expression of L3, and effortlessly the expression of 2.Then, introduce the vectors of L4,L5,L6 and L7, do the same thing—establishment of the vectors' equal—and we can obtain the similar for equals, put them together and differentiate them, we can get equals as follows:

$$-\omega_1 l_2 \sin\theta_1 = -\omega_2 l_3 \sin\theta_2 + v_3 \cos\theta_2 \tag{2}$$

$$-\omega_1 l_2 \cos\theta_1 = \omega_2 l_3 \cos\theta_2 + v_3 \sin\theta_2 \tag{3}$$

$$\omega_2 l_6 \sin\theta_2 - \omega_5 l_7 \sin\theta_5 = 0 \tag{4}$$

$$-\omega_2 l_6 \cos\theta_2 + \omega_5 l_7 \cos\theta_5 = v_5 \tag{5}$$

Here's the matrix multiplication form of them:

$$\begin{bmatrix} \cos\theta_2 & -l_3\sin\theta_2 & 0 & 0 \\ \sin\theta_2 & l_3\cos\theta_2 & 0 & 0 \\ 0 & l_6\sin\theta_2 & -l_7\cos\theta_5 & 0 \\ 0 & l_6\cos\theta_2 & -l_7\cos\theta_5 & 1 \end{bmatrix} \begin{bmatrix} v_3 \\ \omega_2 \\ \omega_5 \\ v_5 \end{bmatrix} = \omega_1 \begin{bmatrix} -l_2\sin\theta_1 \\ l_2\cos\theta_1 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

After this, differentiate these formulas again to prepare for the MATLAB programming procedure.

$$-l_2\alpha_2\sin\theta_1 - \omega_1^2 l_2\cos\theta_1 = \alpha_3\cos\theta_2 - v_3\omega_2\sin\theta_2 - l_3\alpha_2\sin\theta_2 - v_3\omega_2\sin\theta_2 - \omega_1^2 l_3\cos\theta_2 \tag{7}$$

$$l_2\alpha_2\cos\theta_1 - \omega_1^2 l_2\sin\theta_1 = \alpha_3\sin\theta_2 + v_3\omega_2\cos\theta_2 + l_3\alpha_2\cos\theta_2 + v_3\omega_2\cos\theta_2 - \omega_1^2 l_3\sin\theta_2 \tag{8}$$

$$l_6\alpha_2 sin\theta_2 + \omega_2^2 l_6 cos\theta_1 - l_7\alpha_5 sin\theta_5 - l_7\omega_5^2 cos\theta_5 = 0 \tag{9}$$

$$-l_6\alpha_2\cos\theta_2 + \omega_2^2 l_6\sin\theta_1 + l_7\alpha_5\cos\theta_5 - l_7\omega_5^2\sin\theta_5 = 0 \tag{10}$$

Here's the matrix multiplication form of them:

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$$\begin{bmatrix} \cos\theta_2 & -l_3 sin\theta_2 & 0 & 0 \\ \sin\theta_2 & l_3 cos\theta_2 & 0 & 0 \\ 0 & l_6 cos\theta_2 & -l_7 cos\theta_5 & 0 \\ 0 & l_6 sin\theta_2 & -l_7 cos\theta_5 & 1 \end{bmatrix} \begin{bmatrix} a_3 \\ \alpha_2 \\ \alpha_5 \\ a_5 \end{bmatrix} = \begin{bmatrix} 2\omega_2 \sin\theta_2 & \omega_2 l_3 cos\theta_2 & 0 & 0 \\ -2\omega_2 \cos\theta_2 & \omega_2 l_3 sin\theta_2 & 0 & 0 \\ 0 & -l_6\omega_2 cos\theta_2 & l_7\omega_5 cos\theta_5 & 0 \\ 0 & l_6\omega_2 sin\theta_2 & -l_7\omega_5 cos\theta_5 & 0 \end{bmatrix} \begin{bmatrix} v_3 \\ \omega_2 \\ \omega_5 \\ v_5 \end{bmatrix} + \omega_1 \begin{bmatrix} -l_2\omega_1 sin\theta_1 \\ -l_2\omega_1 cos\theta_1 \\ 0 \\ 0 \end{bmatrix} \quad (11)$$

4. The simulating MATLAB programming design

The significance of introducing MATLAB can be manifested in the demand of the kinematic analysis curve, which can provide a strong foundation for the designing process of the most essential part of the whole slotting mechanism, the cam mechanism. With the assistance of the pictograph, reliable reference for the cam's kinematic design and analysis can be gained. The programming procedure is as follows.

By utilizing trigonometric and vector, we can gain graphs as follows:

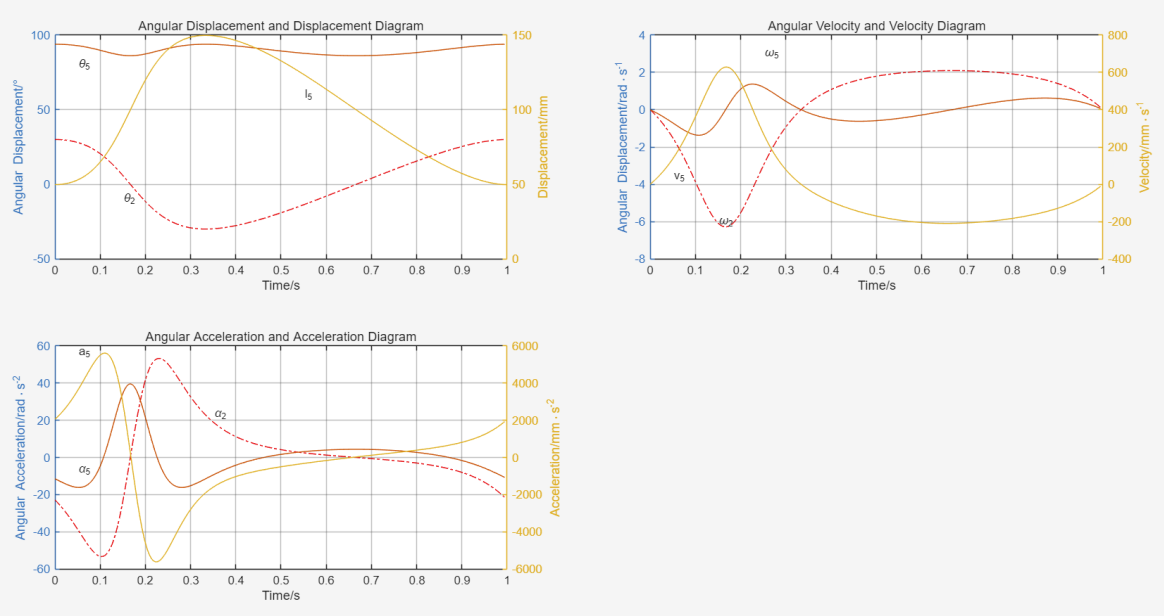


Figure 6. The simulating MATLAB graph

After analyzing the process of the kinematic curve, the reference for researching the most important component, the cam mechanism, is valid and reliable. The cam mechanism is responsible for the work piece's feeding process, and once the crank rotates one full circle, the cutting head slots reciprocate once. And given that the cutting head is moving more constant from 0.5s to 0.9 s in one period, the feeding process should be done from 0.4s to 0.4s meanwhile intermittently space 0.1 seconds to guarantee the safety for the whole mechanism. Specifically, to satisfy the demand above, the programming procedure is suggested to make the overall feeding process in 1 second, with the former 0.4 seconds the mechanism is fed with uniform speed and the latter 0.6 seconds with 0 feeds. This relationship between the follower displacement an the cam rotation angle can be manifested by introducing MATLAB, and the detail parameters and stats are as follows.

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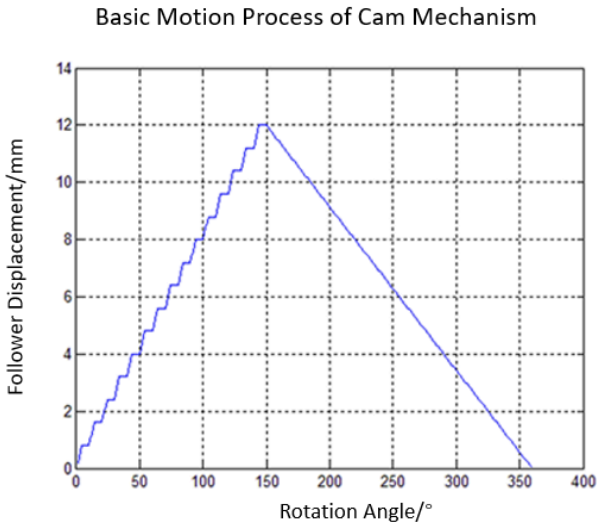


Figure 7. Design and analysis of cam mechanism

This mechanism in the period above slots 15 times and has an overall feeding mass of 12mm, and from 15 seconds to 36 seconds the cam returns to a uniform speed which achieves the standard mentioned above. Finally, to clarify and ascertain the cam profile of the in-line knife-edge translating follower disk cam mechanism, we need to design the base circle's radius as 50mm, and with the assistance of MATLAB software this cam contour can be precisely drawn under the polar coordinate. The sketch map is as follows.

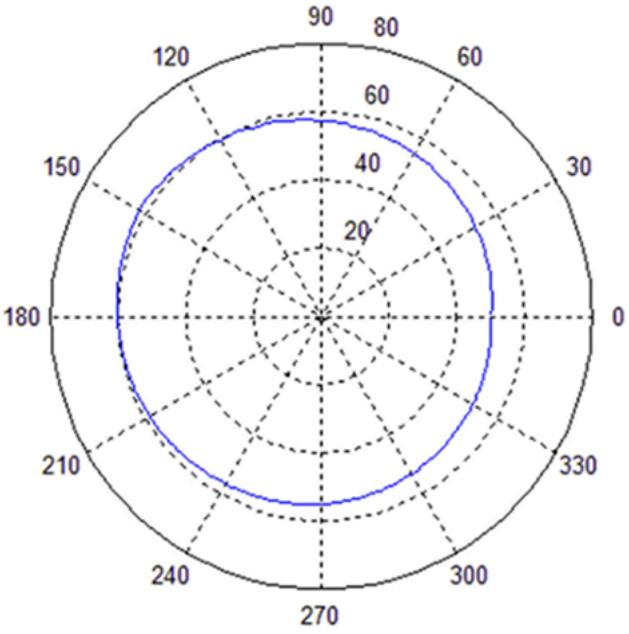


Figure 8. Cam profile in MATLAB software

5. Conclusion

The eternal goal of this research is to develop a reliable mechanism that can be implemented to slotting machine, meanwhile durability and efficiency should be guaranteed. This paper put forward

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a design of coordination of numerous mechanisms which can be categorized as the gear reduction mechanism, the slotting mechanism and the work piece feeding mechanism. The elucidation of the selection of the sub-mechanism of the main mechanism has been demonstrated in this article as the practical implementation of the principle of placing the demand and standard of the overall mechanism in the first place, making the selection of each rational, reasonable and most importantly, suitable.

By utilizing the programming language MATLAB, the kinematic analysis can be manifested in the form of pictograph, and the simplification of the process makes the design of the most dispensable part—the cam mechanism obvious and virtual. Eventually, in the practice, the final selection of the 3 main mechanism is as follows: the V-belt transmission mechanism for reduction, the rotating guide bar mechanism for reciprocating slotting mechanism, and the cam mechanism for the work piece feeding mechanism. This design can fulfill the original demand to the greatest extent possible

Further work needs to be done on optimizing the design to guarantee cost-effectiveness and reforming the working environment of the machine. If necessary, the programming algorithm could also be improved.

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