On the Analysis of an Innovative Mechanism for Wire Electrical Discharge Machine

Feng-Ming Ou, Jen-Yu Liu, and Mei-Hsueh Chen

***Abstract*—The purpose of this paper is to propose an innovative mechanism of wire electrode system and to analyze its kinematic motion of a wire electrical discharge machine (WEDM) for the basis of engineering application. Based on the modular concept, the presented mechanism can be applied to manufacture complicated surfaces. An example for a part with conical surface is also simulated for validation. The result shows that the innovative mechanism will be beneficial to intricate parts manufacturing by WEDM.**

***Index Terms*—innovative mechanism, WEDM, kinematic analysis**

I. INTRODUCTION

According to literature [1], the micro-systems technology applications market in 2004 from 33.5 billion to forecast growth in 2009 of 57.1 billion. In the future, the products of consumer electronics, telecommunications, health medical, nanotechnology, and other related components and microscopic molding market demand is expected to continue to grow. However, when the sizes of products enter into micro-nano level, the design for related products of micro-system will be limited to the ability of micro-manufacturing. In order to manufacture more complex geometrical shape of the product, it must integrate variety of manufacturing method and spend a substantial cost. The working principle of WEDM is the electrode wire feds continually then the melting heat generated from discharge sparks will remove the unwanted materials and makes work-piece formed. During this process, there is no cutting force generated and no electrode consumption problems occur. In recent years, the diameter of wire electrode for Micro-WEDM has been reduced to 0.02mm and some practical applications can be found in micro manufacturing field. Owing to no electrode consumption problem in WEDM, it might be more suitable to manufacture the products with micro features for micro-system technology market. Accordingly, the main purpose of this paper is to propose an innovative mechanism based on modular concept, so as to realize the intricate parts manufacturing by WEDM. An analytical method is established and a simulative example for manufacturing a part with conical surface is used to demonstrate the process motion of this mechanism.

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II. EXISITING CONFIGURATIONS

At present, most types of WEDM are vertical ones and the machining process is carried out by actuating five linear axial motions, i.e. X, Y, Z, U, and V axes. Figure 1 shows the sketch of existing configurations [2], the orientation of wire electrode is guided by the relative motion between UV and XY planes, and two guide-blocks are used to adjust the Z-axis distance for manufacturing. Due to the design of five translational driven axes, such a configuration limits the range of orientation of wire electrode, so usually it applies to make the components of gear or die with simple geometry profiles. If the upper and lower guides have the same movement parallel to XY or UV planes, the work-piece can be cut into column shapes with the same profile at the top and bottom, i.e. 2-D structure, as shown in Figure 2(a). Figure 2(b) shows a part with ruled surface and different top/bottom profiles by moving the upper/lower guides inconsistently [3].

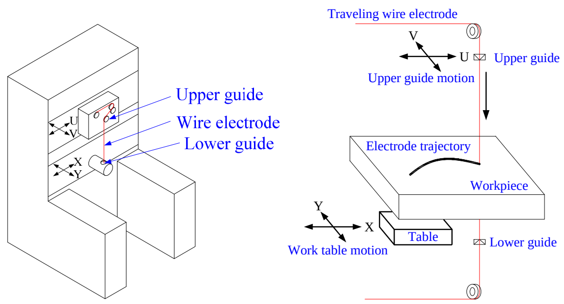


Figure 1 5-axis WEDM structure [2]

(a) 2-D structure

(b) Different top/bottom profile

Figure 2 Parts made by existing 5-axis WEDM [3]

Since the supply and feed systems for wire electrode are coupled with the structure of the machine which possesses five translational degrees of freedom, the feasible machining area is limited. Only 2-D and ruled surface components with axial symmetry profile can be manufactured each time. Re-clamping the work–piece or integrating other processes is inevitable for more complex profile of micro-components, however, the clamping and calibration for the work-piece are not convenient while process changing. Therefore, the difficulties of re-manufacture are increased.

In 2005, Liao et al [4-5] proposed a wire electrode mechanism for micro-WEDM, as shown in Figure 3, which can be applied to manufacture micro work-piece with complex profile. The idea is that the feeding and orientating of wire electrode are designed on a common board. Thus, such a mechanism can be mounted to a three-axis machine. By considering special wire electrode feed planning and orientations adjustment, this mechanism can be used in vertical, horizontal, and tilt wire machining as shown in Figure 4. However, when the orientation changing of wire electrode is needed, the process should be stopped for adjusting the relevant mechanism. Accordingly, once a part manufacturing needs to change the orientation of wire electrode, the adjustment steps will make the whole machining process time-consuming and cumbersome. Moreover, the accuracy of machining is hard to maintain because of the orientation settings, which may easily generate errors due to manual operation.

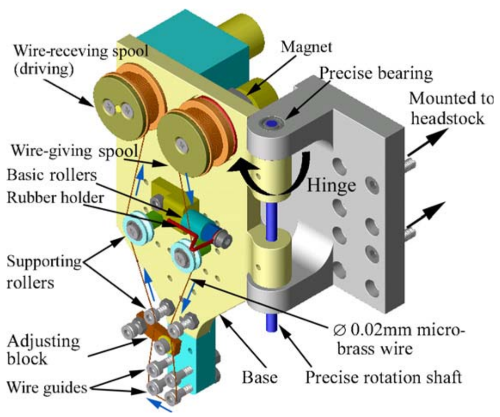


Figure 3 Wire electrode guide mechanism [4]

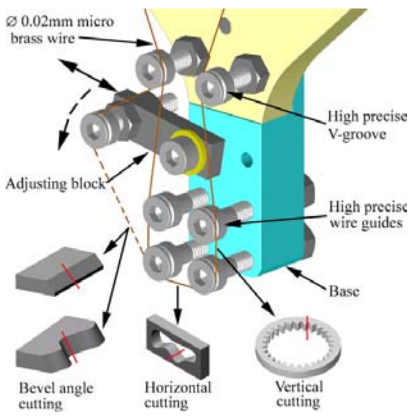


Figure 4 Cutting applications [4]

III. Innovative Mechanism

In 2006, by re-concerning the five degrees of freedom, Ou et al. [6] presented an innovative mechanism module with two rotary axes for wire electrode, as shown in Figure 5.

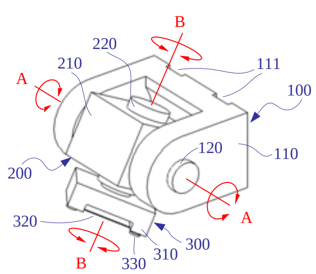
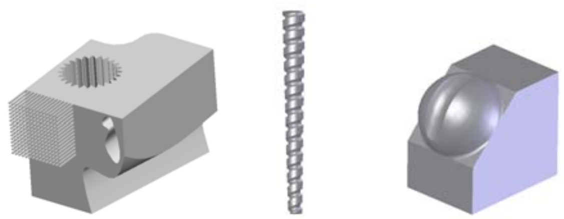


Figure 5 Innovative mechanism module for wire electrode [6]

The purpose is guiding the wire electrode to any spatial orientations. Similar with Liao's mechanism [4], this module can be mounted to a three-axis machine. And, the two rotary axes together with three linear drivers in the machine can achieve any orientations of wire electrode. Therefore, the new 5-axis WEDM with this wire electrode mechanism module will have more flexibility and spaces of machining than the conventional 5-axis ones. The module consists of a unit (100) with a rotary driving shaft A, a unit (200) with a rotary driving shaft B orthogonal with shaft A, and a unit (300) with driving unit of wire electrode, respectively. The unit (100) consists of a U shaped component (110) and a direct drive motor set (120) for shaft A. The unit (200) consists of a box structure (210) and a direct drive motor set (220) for shaft B. The unit (300) is a set composed of feeding and packing wire components (not shown) and some guide wheels (330), and which are all mounted on a base plate (310). These components in unit (300) should be arranged properly to generate a uni-axial wire discharge machining area. The unit (300) is integrated with the drive motor set (220), so that the wire electrode (320) can be rotated and oriented with respect to the shaft B. The box structure (210), used for supporting the set (220) to drive the wire electrode unit (300), can be driven by means of direct drive motor set (120). Hence, the wire electrode (320) also can be rotated and oriented with respect to shaft A. The features (111) of U shaped component (110) are used for installation with the Z-axis feed drive system of a machine tool. When the shaft B is driven alone, the wire electrode (320) will be able to achieve vertical, horizontal, or any tilt angle orientations for the cutting action. Similarly, when the shaft A is driven alone, the wire electrode can achieve any pitch angle orientations for the cutting action. And, when shafts A and B are driven simultaneously, arbitrary cutting orientations can be reached. Once the innovative module is mounted to a machine with three linear feed drive systems, it can satisfy the machining requirements of micro-parts with complex profile. For example, a ruled surface part with different orientation, a part with spiral shape, and a part with freeform surface, respectively, as shown in Figure 6.



(a) ruled surface (b) spiral shape (c) freeform surface

Figure 6 The feasible machining geometric features by the innovative mechanism

IV. Kinematic Analysis

A. Coordinate transformation matrix

Figure 7 shows the new configuration of 5-axis WEDM, which the module mounted to the Z-axis of a machine structure with three linear feed drive systems, i.e. X, Y, and Z axes.

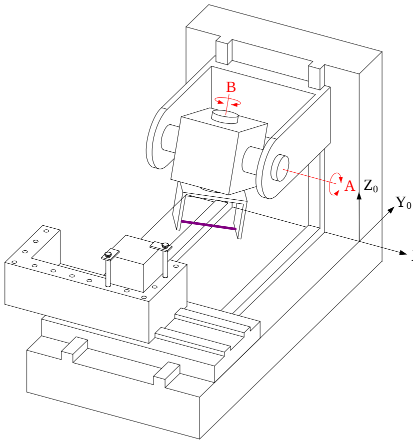
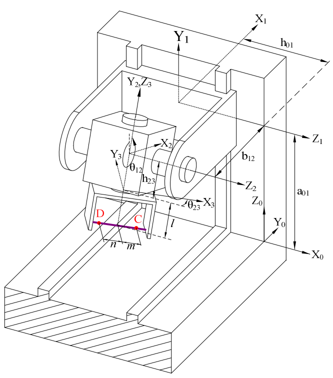
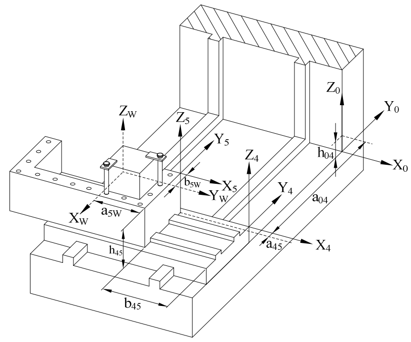


Figure 7　A new configuration of 5-axis WEDM

Figure 8 shows the coordinate systems for the proposed configuration. In Figure 8(a), coordinate $(X,Y,Z)_0$ is the fixed coordinate attached to the frame of machine, $(XYZ)_1$is the moving coordinate attached to the U shaped component and the origin located on its geometric center. The U shaped component is installed to slide along with the Z_0 direction of machine frame. h_{01} is the length between X_1 axis and Y_0 axis and a_{01} refers to the module movement along Y_1 axis. The moving coordinate $(XYZ)_2$ is attached on the A-axis driving unit, of which the Z_2 axis and A-axis are collinear and parallel to Z_1 axis with a distance of b_{12}. θ_{12} is the angular displacement from Y_1 to Y_2 with respect to Z_2 axis. Again, the moving coordinate $(XYZ)_3$ is attached on the B-axis driving unit which rotates with respect to A axis. Z_3, Y_2, and B axes are collinear, and the length h_{23} is the distance between the origins of $(XYZ)_3$ and $(XYZ)_2$. The angular displacement θ_{23} is the rotational angle of B axis. The wire electrode is paraplell to X_3 axis with a distance l and the length CD is the feasible machining area of wire electrode. Points C and D can be described from the origin O_3 with a distance m and n respectively. Figure 8(b) shows the coordinate definition from the machine frame to work-piece. Three moving coordinates $(XYZ)_4$, $(XYZ)_5$, and $(XYZ)_W$ are attached to saddle, table, and work-peice, respectively, and they are all parallel to the fixed coordinate $(XYZ)_0$. a_{04} is the saddle movement along Y_0 axis and b_{45} is the table movement along X_0 axis. Parameters a_{45} and h_{45} are the distances between coordinates $(XYZ)_4$ and $(XYZ)_5$ along Y and Z directions respectively. And, a_{5W} and b_{5W} are the position parameters for clamping work-piece. Here, a set of values of these parameters for simulation is listed in table 1 and table 2.



(a) coordinate systems from frame to the innovative module



(b) coordinate systems from frame to work-piece

Figure 8　Coordinate systems

Table 1　The simulated dimensions of machine

h_{01}	b_{12}	h_{23}	h_{04}	h_{45}	a_{45}	a_{5W}	b_{5W}	l
75	60	21	10	30	10	39	11	24.5

Table 2　The initial locations

a_{01}	θ_{12}	θ_{23}	a_{04}	b_{45}
145	0˚	0˚	110	0

According to the principle of Coordinate Transformation [7], the transfer matrix T_{03} can be obtained as:

$$T_{03} = \begin{bmatrix} C\theta_{23} & -S\theta_{23} & 0 & -h_{01} \\ C\theta_{12}S\theta_{23} & C\theta_{12}C\theta_{23} & -S\theta_{12} & S\theta_{12}\ h_{23} - b_{12} \\ S\theta_{12}S\theta_{23} & S\theta_{12}C\theta_{23} & C\theta_{12} & -C\theta_{12}\ h_{23} + a_{01} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where Sθ means sinθ and Cθ means cosθ. Similarly, the transformation matrix T_{0W} is:

$$T_{0W} = \begin{bmatrix} 0 & 1 & 0 & -a_{5W} - b_{45} \\ -1 & 0 & 0 & -b_{5W} - a_{45} - a_{04} \\ 0 & 0 & 1 & h_{45} + h_{04} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

The position vectors of points C and D in $(XYZ)_3$ are:

$$\boldsymbol{R}_3^C = m\ \boldsymbol{i}_3 - l\ \boldsymbol{k}_3 \quad (3)$$

$$\boldsymbol{R}_3^D = -n\ \boldsymbol{i}_3 - l\ \boldsymbol{k}_3 \quad (4)$$

Equations (3) and (4) can be expressed in $(XYZ)_0$ as:

$$\begin{aligned} \boldsymbol{R}_0^C &= [T_{03}]\ \boldsymbol{R}_3^C \\ &= (mC\theta_{23}-h_{01})\ \boldsymbol{i}_0 + (mC\theta_{12}S\theta_{23}+lS\theta_{12}+h_{23}S\theta_{12}-\mathbf{b}_{12}) \\ &\quad \boldsymbol{j}_0 + (mS\theta_{12}S\theta_{23}-lC\theta_{12}-h_{23}C\theta_{12}+a_{01})\ \boldsymbol{k}_0 \end{aligned} \quad (5)$$

$$\begin{aligned} \boldsymbol{R}_0^D &= [T_{03}]\ \boldsymbol{R}_3^D \\ &= (-nC\theta_{23}-h_{01})\ \boldsymbol{i}_0 + (-nC\theta_{12}S\theta_{23}+lS\theta_{12}+h_{23}S\theta_{12}-\mathbf{b}_{12}) \\ &\quad \boldsymbol{j}_0 + (-nS\theta_{12}S\theta_{23}-lC\theta_{12}-h_{23}C\theta_{12}+a_{01})\ \boldsymbol{k}_0 \end{aligned} \quad (6)$$

From Equations (5) and (6), the vector of wire electrode $\boldsymbol{R}_0^{CD}$ in $(X,Y,Z)_0$ can be obtained as follows:

$$\begin{aligned} \boldsymbol{R}_0^{CD} = \boldsymbol{R}_0^C - \boldsymbol{R}_0^D &= (m+n)C\theta_{23}\ \boldsymbol{i}_0 + (m+n)C\theta_{12}S\theta_{23}\ \boldsymbol{j}_0 + \\ &\quad (m+n)S\theta_{12}S\theta_{23}\ \boldsymbol{k}_0 \end{aligned} \quad (7)$$

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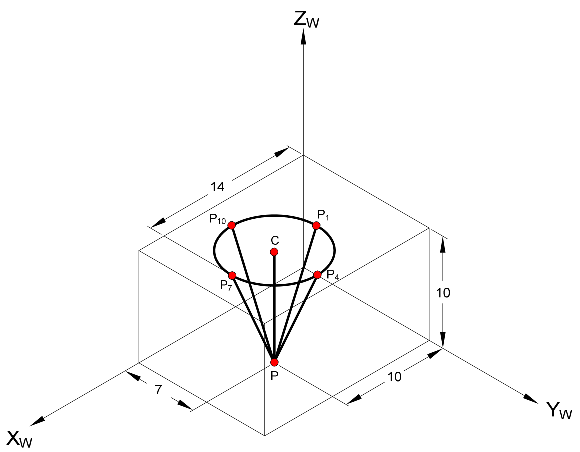
Then, the unit vector U_0^{CD} of vector R_0^{CD} is:

$$U_0^{CD} = C\theta_{23}\, \boldsymbol{i}_0 + C\theta_{12} S\theta_{23}\, \boldsymbol{j}_0 + S\theta_{12} S\theta_{23}\, \boldsymbol{k}_0 \qquad (8)$$

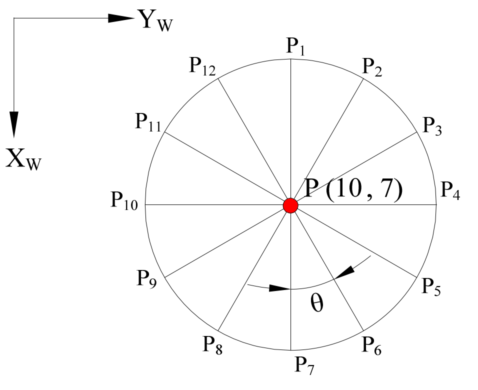
Once the cutting location of a work-piece is given, it can be expressed as a known unit vector and let the x, y , and z components of this known unit vector equal to the ones of Equation (8), then the values of angular displacements θ_{12} and θ_{23} can be solved. Moreover, let the point C coincident to the point on the known cutting line vector, the required X, Y, and Z translational movements for the table and the module can be obtained.

B. A simulated example

In this study, a part with conical surface is given to verify the presented model for kinematic analysis of the mechanism. In Figure 9(a), point P is the vertex and P_1 is an abritray point on the base circle with radius 4 mm of this cone. Assume points P and P_1 in the coordinate $(XYZ)_W$ are (10, 7, 0) and (6, 7, 10) respectively. Figure 9(b) shows the circumference of the base circle and which is divided into 12 equal parts by the points P_1 to P_{12}. For brief explanation, below it shows the calculation for cutting line vectors **PP**$_1$, **PP**$_4$, **PP**$_7$, and **PP**$_{10}$, respectively. The position vectors of points P, P_4, P_7, and P_{10}, in the coordinate $(XYZ)_W$ are obtained as follows:



(a) dimensions of a work-piece for making a conical part



(b) circumference is divided into 12 equal parts

Figure 9 Machining simulation example

$$R_W^{P} = 10\, \boldsymbol{i}_W + 7\, \boldsymbol{j}_W \qquad (9)$$

$$R_W^{P_1} = 6\, \boldsymbol{i}_W + 7\, \boldsymbol{j}_W + 10\, \boldsymbol{k}_W \qquad (10)$$

$$R_W^{P_4} = 10\, \boldsymbol{i}_W + 11\, \boldsymbol{j}_W + 10\, \boldsymbol{k}_W \qquad (11)$$

$$R_W^{P_7} = 14\, \boldsymbol{i}_W + 7\, \boldsymbol{j}_W + 10\, \boldsymbol{k}_W \qquad (12)$$

$$R_W^{P_{10}} = 10\, \boldsymbol{i}_W + 3\, \boldsymbol{j}_W + 10\, \boldsymbol{k}_W \qquad (13)$$

The vectors in Equations (9) to (13) can be transformed to the coordinate system $(XYZ)_0$ and expressed as follows:

$$R_0^{P} = -32\, \boldsymbol{i}_0 - 141\, \boldsymbol{j}_0 + 40\, \boldsymbol{k}_0 \qquad (14)$$

$$R_0^{P_1} = -32\, \boldsymbol{i}_0 - 137\, \boldsymbol{j}_0 + 50\, \boldsymbol{k}_0 \qquad (15)$$

$$R_0^{P_4} = -28\, \boldsymbol{i}_0 - 141\, \boldsymbol{j}_0 + 50\, \boldsymbol{k}_0 \qquad (16)$$

$$R_0^{P_7} = -32\, \boldsymbol{i}_0 - 145\, \boldsymbol{j}_0 + 50\, \boldsymbol{k}_0 \qquad (17)$$

$$R_0^{P_{10}} = -36\, \boldsymbol{i}_0 - 141\, \boldsymbol{j}_0 + 50\, \boldsymbol{k}_0 \qquad (18)$$

Then, the vectors $R_0^{PP_1}$, $R_0^{PP_4}$, $R_0^{PP_7}$, and $R_0^{PP_{10}}$ are:

$$R_0^{PP_1} = -4\, \boldsymbol{j}_0 - 10\, \boldsymbol{k}_0 \qquad (19)$$

$$R_0^{PP_4} = -4\, \boldsymbol{i}_0 - 10\, \boldsymbol{k}_0 \qquad (20)$$

$$R_0^{PP_7} = 4\, \boldsymbol{j}_0 - 10\, \boldsymbol{k}_0 \qquad (21)$$

$$R_0^{PP_{10}} = 4\, \boldsymbol{i}_0 - 10\, \boldsymbol{k}_0 \qquad (22)$$

And, the unit vectors $U_0^{PP_1}$, $U_0^{PP_4}$, $U_0^{PP_7}$, and $U_0^{PP_{10}}$ can be obtained as:

$$U_0^{PP_1} = (-4\, \boldsymbol{j}_0 - 10\, \boldsymbol{k}_0)/\sqrt{116} \qquad (23)$$

$$U_0^{PP_4} = (-4\, \boldsymbol{i}_0 - 10\, \boldsymbol{k}_0)/\sqrt{116} \qquad (24)$$

$$U_0^{PP_7} = (4\, \boldsymbol{j}_0 - 10\, \boldsymbol{k}_0)/\sqrt{116} \qquad (25)$$

$$U_0^{PP_{10}} = (4\, \boldsymbol{i}_0 - 10\, \boldsymbol{k}_0)/\sqrt{116} \qquad (26)$$

From Equations (8) and (23) to (26), four sets of A-axis and B-axis angular displacement can be solved, and they are (θ_{12}, θ_{23})=(248.2°, 90°), (θ_{12}, θ_{23})=(270°, 111.8°), (θ_{12}, θ_{23})=(291.8°, 90°), and (θ_{12}, θ_{23})=(270°, 68.2°) for line vectors **PP**$_1$, **PP**$_4$, **PP**$_7$, and **PP**$_{10}$, respectively. Then, the wire electrode can be driven by A and B axes to the correct initial orientation and begins to manufacture the work-piece. Here, vector **PP**$_1$ is taken as an example to show the calculation of X, Y, and Z translational movements. The length of **PP**$_1$ is:

$$PP_1 = \left|\boldsymbol{R}_0^{PP_1}\right| = \sqrt{116} \tag{27}$$

Therefore, the length of wire electrode must exceed this value and we assume $m=n=\sqrt{116}/2$. When the point D on the wire electrode is moved from the initial position to the same height of point P_1, then the table should move the work-piece to let point P_1 and point D meet together. Accordingly, the position vector of point D in the coordinate $(XYZ)_0$ is:

$$R_0^D = -75\,\boldsymbol{i}_0 - 100.2463\,\boldsymbol{j}_0 + 166.8971\boldsymbol{k}_0 \tag{28}$$

And, according to Equations (15) and (28), the X and Y movements of table and Z movement of the module can be obtained as follows:

$$\Delta X_0 = (-75) - (-32) = -43 \tag{29}$$

$$\Delta Y_0 = (-100.2463) - (-137) = -36.7537 \tag{30}$$

$$\Delta Z_0 = 166.8971 - 50 = 116.8971 \tag{31}$$

Similarly, the cases for the cutting line vectors $\mathbf{PP}_4$, $\mathbf{PP}_7$, and $\mathbf{PP}_{10}$ can be carried out respectively.

By using the cosmos function of Solidworks software, it is proved that the wire electrode can be guided to coincident with the line vectors $\mathbf{PP}_1$, $\mathbf{PP}_4$, $\mathbf{PP}_7$, and $\mathbf{PP}_{10}$, respectively. Figure 9 shows the simlation results. Therfore, for cutting a part with a complex profile, each location parameters on the machining path can be obtained by the above-mentioned methods.

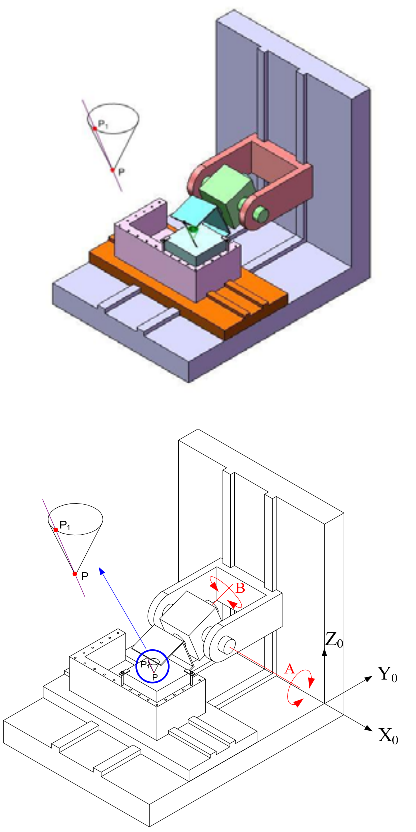


Figure 9 Simulated result by Solidworks

V. Conclusion

Two existing configurations of WEDM are explored and introduced in this study. By analyzing the degrees of freedoms of existing designs, an innovative mechanism module of wire electrode with two rotating shafts is proposed. This module can be installed on a conventional 3-axis machine structure. By using the three axial motions provided by the machine and two rotational motions provided by this innovative module, the WEDM can manufacture a complexity geometric shape work-piece. A simulation example for manufacture a part with conical shape is demonstrated in this paper. This example verifies the module can meet the required position of machining. The results of this paper show this innovative module indeed has the advantages of multi-directional and multi-orientation for wire electrode. It can provide a new configuration choice to manufacture micro-components with complex profile in the future.

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