Preliminary Kinematics Design of 5-axis Micromilling Machine

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Preliminary Kinematics Design of 5-axis Micromilling Machine

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ABSTRACT

5-axis micromilling technology is increasing since 1990's to produce 3D product in micro even nano dimension, which use in most of automotive industry, house appliance, airplane components, micro medical equipment, electronic industry, etc. Highest accuracy is the main goal of every 5-axis micromilling.
To design a 5-axis micromilling machine, the first thing to do is to determine the machine construction based on the machine requirement. Most of 5-axis machine widely used has three translation axis XYZ and two rotational axis of ABC. This paper present a conceptual mechanical design evaluation for three type of 5-axis micromiling construct with avaliable components.
Machining accuracy is depending on some factor, one of the factors is the machine geometry that related to rigidity and construction strength. So, the strength analysis of 5-axis micromilling design for the construction must be done with 5.5 N cutting force. The simulation and analysis is perform using CAE software.
To translate the command from CAM system (CL data) into machine movement is done by transforming the machine kinematic into matrices space using the kinematic engine. The kinematic engine for 5-axis micromilling is successly develop and ready to implemented in a postprocessor.

Keywords

5-axis micromilling, design evaluation, kinematic design

1. INTRODUCTION

Nowadays, the products are becoming more varies, aesthetic and futuristic. Products with complex shape and sometimes in a micro even nano dimension are found in most of automotive industries, house appliances, airplane components, micro medical equipments, electronic industry and etc. In this term, 5-axis micromilling is becoming attractive solution to achieve such product. The technology of 5-axis micromilling is increasing since 1990's and even growing in the past few years. The trend of every machining technology is to increase the accuracy of the product.

Generally, there are several types of 5-axis micromilling machine that is classified according to the number of translation and rotational axis. However the most commonly used is the three translation axes XYZ with two rotary axes of AB, AC, or BC axis. The combination of those axis resulting several types of 5-axis milling machine known as table-tilting type, spindle-tilting type and table/spindle-tilting type [1,2,3,4]. Young-bong Bang, Kyung-min Lee and Seungryul Oh [5] shows that a 5-axis micromilling can be constructed at a low cost with commercially available parts and the constructed micromilling machine is capable of producing practical micro parts.

To build a 5-axis micromilling machine, the main system components which are kinematics and construction, and the control system have to be designed with respect to the specified working conditions. Dehong Huo, Kai Cheng and Frank Wardle [6, 7] explained that there are three major issues to design a 5-axis micromilling: motion accuracy, dynamic stiffness and thermal stability. So, it is important to analyze and simulate the machine construction strength which can be done using Computer Aided Engineering (CAE) software. The machine dynamic performance depending not only on the mechanical structure and components but also the control system and electronic drives.

The next step is to formulate detail of kinematics model of the machine, that translate the command from a CAM system in a form of CL (cutter location)-file, to become NC command for the movement of each axis. Bohez [1] classify the 5-axis milling according to combination of linear and rotary axes and he shows the kinematic chain of all groups that he has classified. R-S Lee and C-H She [2] proposed kinematics model of machine postprocessing for three type 5-axis machine tools using homogeneous coordinate transformation matrix. Chen-Hua She and Zaho-Tang Huang [3] also proposed proposed kinematics model of machine postprocessing for three type 5-axis machine tools with nutating head and table configuration. Sylvain Lavernhe et.al [8] presents a predictive model of the kinematical behavior during 5-axis machining; the model is use the inverse-time method to coordinate machine-tool axes. He also proposed a predictive model kinematical performance in 5-axis milling within the context of high-speed machining [9]; the proposed model relies on each axis displacement in the joint space of the machine tool and predicts the most limiting axis for each trajectory segment. Lamikiz et.al [10] proposed a methodology for the estimation of the geometrical accuracy using the Denavit and Hartenberg (D-H) formulation. M. Sharif Uddin et.al [11] proposed a simulator and compensation of machining errors in five-axis machining by considering the effect of kinematic errors on the three-dimensional interference of the tool and the workpiece. He found that there are three kinematic error associated with linear axes and eight kinematic errors associated with rotary axes of the machining center, are considered and identified practically by a DBB method. M.Munlin et.al [12] proposed a new algorithm designed for five-axis milling to minimize the kinematics error near the stationary points of the machined surface.

The objectives of this work are to design the mechanical geometry and construction and the kinematics of 5-axis micromilling machine. Three types of commonly used 5-axis micromilling cofiguration are evaluated.

2. DESIGN OF 5-AXIS MICROMILLING

2.1 Types of 5-axis micromilling

Theoritically, there are numerous combination to yield the five-axis machine tools configuration. However as explained above, in practice, the configuration can be classified into three basic types according to the distribution of the two rotational movement units :

1. Table-tilting with two rotation on the table.
2. Spindle-tilting with two rotation on the spindle.
3. Table/spindle tilting with one rotation each on the table and spindle.

In order to build and evaluate the above designs, the following components, which are available in the market, are selected :

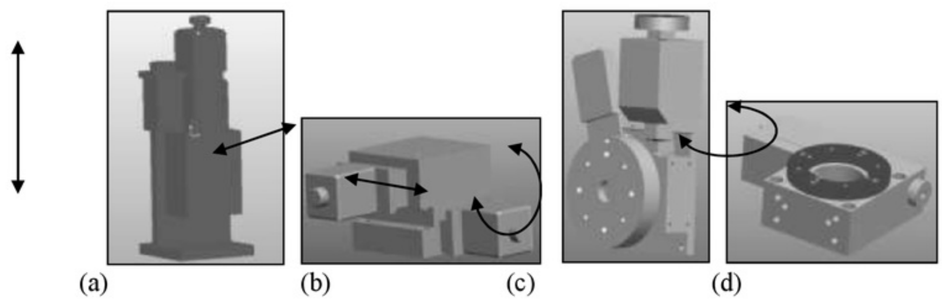
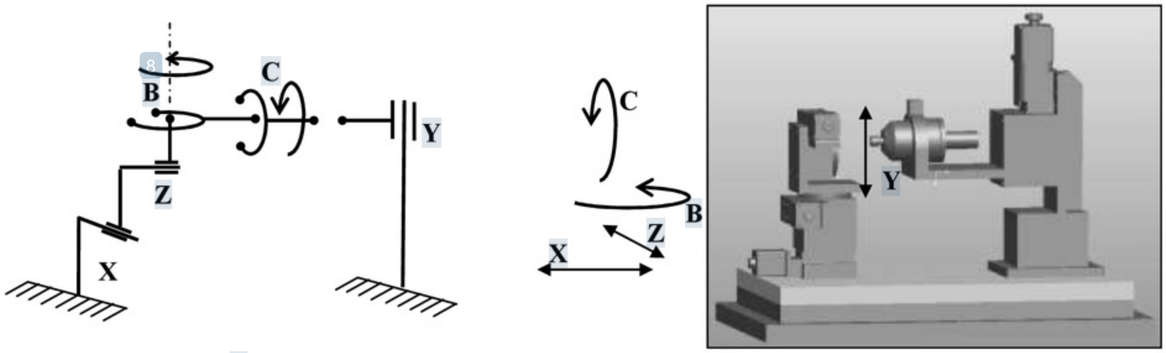


Fig.1 (a) Single Linear Stage, (b) Two Linear Stages which are attached to each other, (c) and (d) Rotary Stage

The specification of the selected components has been verified against the predefiened accuracy (1µm) and possible maximum load (<= 3 kgf).

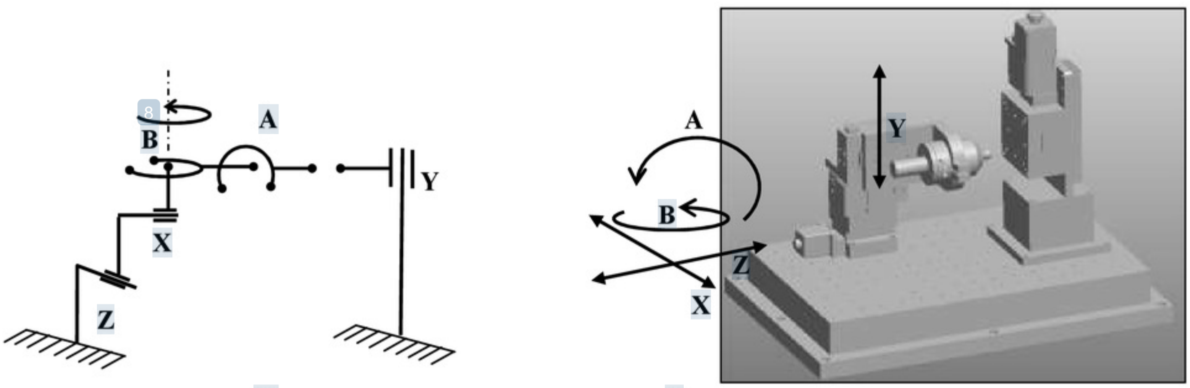
2.2 Possible Kinematics and Construction Design of 5-axis micromilling

The designs of three types of machine mentioned above, using avaliable components is shown in the Fig.2, Fig 3 and Fig.4 .



(a) (b)

Fig.2: a) Schematic of Kinematics model and b) possible Table-tilting design/construction with XYZ and BC axis movement as 1st Alternative.



(a) (b)

Fig.3: a) Schematic of Kinematics model and b) possible Spindle-tilting design with XYZ and AB axis movement as 2nd Alternative.

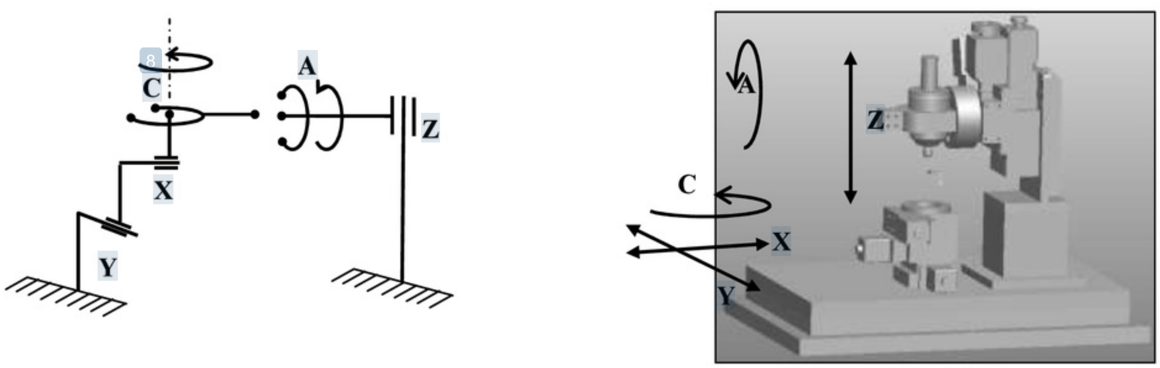


Fig. 4: a) Schematic of Kinematics model and b) possible Table/spindle-tilting with XYZ and AC movement as 3th Alternative.

2.3 Design Evaluation

To evaluate the design alternative, this paper use an Advanced Decision Matrix based on the Robust Decision Making, explained by Ulman [13]. By using this method,it able to compare all the alternative and decide the most satisfaction alternative.

The weightings or scoring to evaluate the design by using the word equation as follow :

Satisfaction = belief that an alternative meets the criteria

Belief = knowledge + confidence.

This virtual sum of knowledge and confidence can be expressed on a Belief Map as a tool to picture and undertand evaluation, see Fig.5. To qualitatively measuring knowledge and confidence is using the scale as shown in Fig.6. The advance

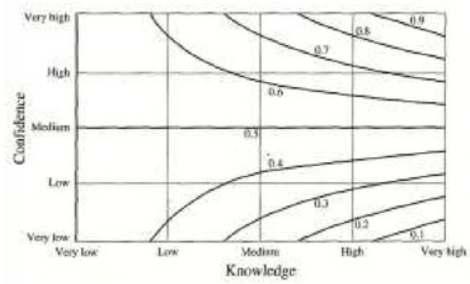


Fig 5: Belief map to weight the design alternative [13]

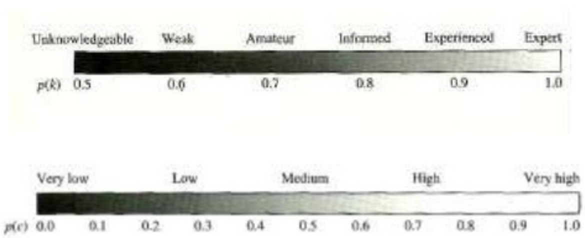


Fig. 6: Scale for qualitatively measuring (a) Knowledge and (b) Confidence [13]

Table 1.Advance decision matrix for 5-axis micromilling design.

Criteria		Importance	Alternatives		
			1st	2nd	3th
1	Position Accuracy within 0,5 nm	15	0,6	0,5	0,6
2	Good construction rigidity	15	0,5	0,3	0,6
3	Low vibration	12	0,4	0,3	0,4
4	Less critical parameter	12	0,3	0,3	0,5
5	Flexibility in movement	12	0,5	0,5	0,5
6	Wide range of working envelop	12	0,3	0,4	0,5
7	Less component	8	0,2	0,2	0,4
8	Easy to assembly	6	0,2	0,3	0,4
9	Easy to maintain	8	0,2	0,3	0,4
		Satisfaction	38,9 %	35,8 %	49,6 %

According to the highest score of satisfaction, the 3th alternative will be the appropriate design for 5-axis micromilling machine. To have a better analysis, the strength of the design construction is simulated using a CAE software, as shown in Fig. 7. The critical point of the whole machine tool is on the component Z axis, about 6.26 x 10^{-2} N/mm^2, the magnitude is still in safe for the operation with 5,5 N of cutting force [14].

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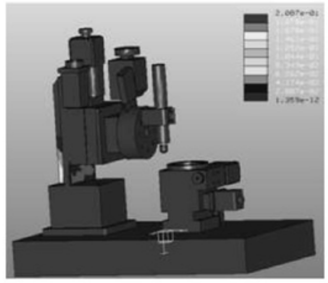


Fig.7: Strength analysis of the 3th alternative design

3. DETAIL KINEMATICS FOR POSTPROCESSING

The kinematic of a machine is a transformation from a point in machine coordinate system (MCS) into the tool coordinate system (TCS) and the workpiece coordinate system (WCS), where the point is move along the coordinate system as an axis vector. The intersection betwen TCS and WCS will caused the machining process, this called Cutter Contact (CC) point. To control the movement of the tool, a set of CC point will computed as a set of Cutter Location (CL) point. Nowdays, the CAM system able to generate the CL file and simulating the cutting process.

But to transform and calculate the CL point to become the axis movement of the machine tools XYZ axis and AC axis, the kinematic engine for each machine tool must be designed. The CL data consist of the position and orientation of the cutter with respect to the workpiece coordinate system as shown in Fig. 8. The point vector is written as $[Q_x\ Q_y\ Q_z\ 1]^T$ as the cutter tip center and vector of form $[K_x\ K_y\ K_z\ 0]^T$ are used to represent direction for homogeneous coordinate notation. The supercript "T" denotes the transposed matrix. The four fundamental transformation matrice used in this paper are as follows :

$$Trans\ a,b,c = \begin{matrix} 1 & 0 & 0 & a \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{matrix} \quad (1) \qquad Rot(X,\varphi) = \begin{matrix} 1 & 0 & 0 & 0 \\ 0 & C\varphi & -S\varphi & 0 \\ 0 & S\varphi & C\varphi & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \quad (2)$$

$$Rot(Y,\varphi) = \begin{matrix} C\varphi & 0 & S\varphi & 0 \\ 0 & 1 & 0 & 0 \\ -S\varphi & 0 & C\varphi & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \quad (3) \qquad Rot(Y,\varphi) = \begin{matrix} C\varphi & S\varphi & 0 & 0 \\ S\varphi & C\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix} \quad (4)$$

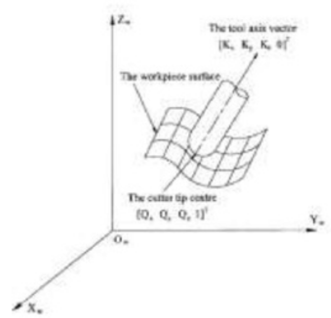
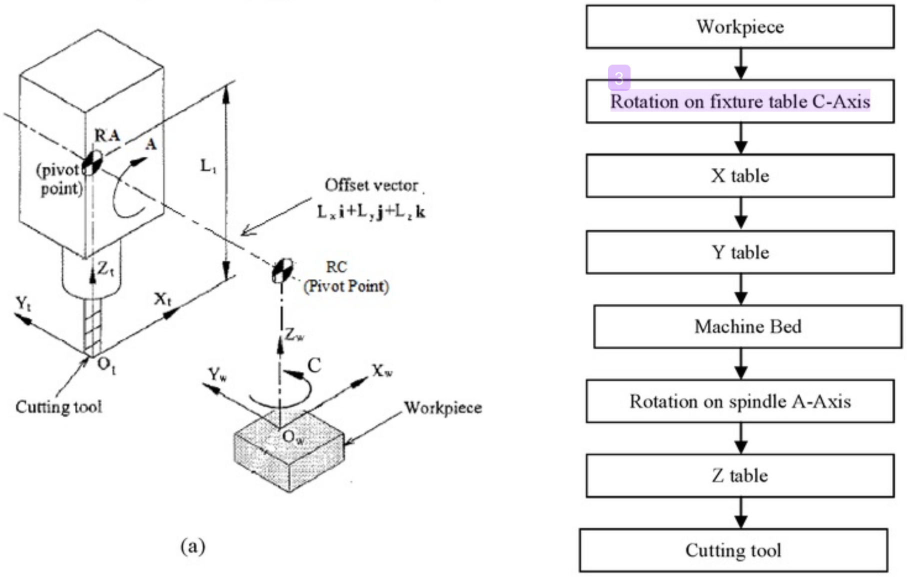


Fig. 8 : Geometric definition of CL data [2]

In this paper, the kinematics engine will design based on a method proposed by R-S Lee and C-H She [2]. The method is using inverse kinematic to establish a mathematical description. They shows three types of 5-axis machine tool of table tilting XYAC-Z, spindle tilting XY-ABZ and table/spindle-tilting XYA-BZ. Since, the 5-axis micromilling design axis is XYC-AZ, then calculating the kinematic equation for NC data is very neccecary.

For the 5-axis micromilling table/spindle-tilting type present in this paper, the coordinate system of $O_wX_wY_wZ_w$ and $O_tX_tY_tZ_t$ are attached to the workpice and the cutting tool, respectively. The coordinate system and the relationship of structural elements of table/spindle-tilting type is shown in Fig 8.



(a) (b)

Fig. 9: (a) Coordinate system and (b) relationship of structural elements of table/spindle-tilting type configuration

The pivot point R_A is located on the A axis arbitrarily and the pivot point RC is the intersection of workpiece rotation and the spindle tilting. The offset vector $L_xi+L_yj+L_zk$ is calculated from the origin O_w to the point RC and the effective tool length, L_t, is the distance between the pivot point RA and the cutter tip center, O_t.

The relative orientation and position of the cutting tool with respect to the workpiece coordinate system can be determine by multiplying the corresponding fundamental transformation matrices in series, and should be equal to the known CL data, $[K_x\ K_y\ K_z\ 0]^T$ and $[Q_x\ Q_y\ Q_z\ 1]^T$. The mathematical expression is described as follows :

$$[K_x\ K_y\ K_z\ 0]^T = \mathrm{Trans}\,(L_x, L_y, L_z)\ \mathrm{Rot}(Z,-\varphi_C)\ \mathrm{Trans}\,(P_x, P_y, P_z)\ \mathrm{Rot}(X,-\varphi_A)[0\ 0\ 1\ 0]^T \qquad (5)$$

$$[Q_x\ Q_y\ Q_z\ 1]^T = \mathrm{Trans}\,(L_x, L_y, L_z)\ \mathrm{Rot}(Z,-\varphi_C)\ \mathrm{Trans}\,(P_x, P_y, P_z)\ \mathrm{Rot}(X,-\varphi_A)[0\ 0\ -L_t\ 1]^T \qquad (6)$$

where φ_A and φ_C are the rotation angles about the X, and Z axes, respectively, and positive rotation is in the direction to advance a right-hand screw in the +X and +Z axis directions. P_x, P_y, P_z are the relative translation distances of the X, Y, and Z tables, respectively. Multiplying equations (5) and (6), yields:

$$\begin{matrix} K_x \\ K_y \\ K_z \\ 0 \end{matrix} = \begin{matrix} S\varphi_A \cdot S\varphi_C \\ -S\varphi_A \cdot C\varphi_C \\ C\varphi_A \\ 0 \end{matrix} \qquad (7)$$

$$\begin{matrix} Q_x \\ Q_y \\ Q_z \\ 1 \end{matrix} = \begin{matrix} -S\varphi_A \cdot S\varphi_C.L_t - P_x.C\varphi_C + P_y.S\varphi_C + L_x \\ S\varphi_A \cdot C\varphi_C.L_t - P_x.S\varphi_C - P_y.C\varphi_C + L_y \\ C\varphi_A.L_t + P_z - L_t \\ 1 \end{matrix} \qquad (8)$$

From the above equations, the rotation angles (φA, φC) and the relative translation distances (Px, Py, Pz) can be solved. On the other hand, the X, Y, Z values of the NC data in programming are obtained using equation (6) under the condition φA = φC = 0, and $[Q_x\ Q_y\ Q_z\ 1]$ T = [X Y Z 1] T since the program coordinate system is coincident with the workpiece coordinate system. This leads to:

$[X\ Y\ Z\ 1]^T = [L_x + P_x,\ L_y + P_y,\ L_z + P_z - L_t]^T$

Thus, the desired equations for NC data of this configuration can be expressed as follows:

$$A = \varphi_A = \arccos(K_Z) \qquad (-\pi/2 \le \varphi_A \le \pi/2) \tag{9}$$

$$C = \varphi_C = \arctan(K_x, K_y) \qquad (-\pi \le \varphi_C \le \pi) \tag{10}$$

$$X = Q_x + L_x\ C\varphi_C - Q_y - L_y\ S\varphi_C + L_x \tag{11}$$

$$Y = -Q_x - L_x\ S\varphi_C + Q_y - L_y\ C\varphi_C - S\varphi_A.L_t + L_y \tag{12}$$

$$Z = Q_z - C\varphi_A.L_t + L_t + L_z \tag{13}$$

The kinematic engine is succesly develop and will be then implemented into a software, known as the postprocessor.

4. CONCLUSION

The conceptual mechanical design for three types alternative of 5-axis micromilling machine with avaliable component is perform using Advanced Decision Matrix Method based on the Robust Decision Making. The highest Satisfaction score indicate that the third alternative, table/spindle-tilting of XYC-AZ axis, is the appropriate design for 5-axis micromilling.

The strength analysis of the design using a CAE software indicate that the construction is safe for 5,5 N of cutting force prediction [14].

To transform the CL data from a CAM system, it is necessary to calculate the kinematic of the machine tools into a mathematical equation that will be implemented in a postprocessor. There are many method to generate the kinematic engine. This paper succesfully develope a kinematic engine for table/spindle-tiling of XYC-AZ using a method proposed by Lee and She [2].

Further research will step on into mechanical prototyping and modelling the postprocessor of kinematic engine.

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