

Offset Algorithm for Compound Angle Machining of Parts when Tool Motion is Unrestricted in Space

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ABSTRACT

Although the performance of CNC machines is accurate, unavoidable human errors at the part loading position have serious repercussions on engine performance.

In the present paper the authors would like to develop an algorithm for error compensation when the tool movement is unrestricted in space. The new solution algorithm will be in terms of the known initial system variables such as the part loading errors, drill tool inclinations, location of spindle etc. This modified paper employs the same principles of inverse kinematics as done in the earlier paper wherein a faulty compound-hole angle axis in space caused by the translational and rotational errors at the part loading position is identified with an imaginary true axis in space by enforcing identity through a modified machine axes taking into effect inclination of the drill tool in space. In the absence of any specific application, this algorithm is verified on Solid Works a commercial CAD tool and found to be correct. An example problem given at the end vindicates this statement.. This new algorithm can also be applied in the design of 2-link 6-DOF robotics manipulator or in CNC machining for contour generation on parts with part loading errors, or in orthopedic operations employing robotic manipulators to assist surgeons.

Key Words: Compound angle, Cylinder head, Cummins engine, Valve angle, Valve seat, robotic manipulator, orthopedic operations.

1 INTRODUCTION

In the current design of Cylinder Head engines, the drill is constrained to move in vertical plane. It is quite possible in the near future to have a redesigned cylinder head with drill axis inclined at any angle in space. A valve job is meant to improve the seal between the valve and the valve seat on the head ensuring sufficient pressure in the

combustion chamber whenever the spark plug fires and so proper valve angles and concentric valve seats are critical to satisfactory performance of engine. Figure 1 shows a schematic of a real part loaded with errors in a fixture. For general kind of compound-angle machining problems, the possible part loading errors are transformed into translation and rotation errors of the compound-angle hole-axis. One widely used procedure to solve them is the error compensation scheme by way of an algorithm. The correction algorithm is loaded into the CNC controller to compute and impart the required corrected movements to the machine axes.

1.1 LITERATURE REVIEW OF PREVIOUS WORK

In multi-axis machining errors are associated with the toolpath generation. Moreton and Durnford [7] developed an algorithm for a three axis-turning center (X, Y and C-axis) which is used for milling surfaces. An algorithm is used to compensate for kinematic and interpolation errors which are compensated in the CNC program. Their algorithm provides the tool diameter and the errors in function of the tool diameter, number of Cutter Location points and toolpath length. Balsamo et al. [1] suggested the use of techniques based on ball plate to determine parametric errors in CMM machines Hwang [4] used a kinematic model to derive equations in closed form for the real toolpath curve for a 4-axis milling machine. For cases when the cutter workpiece interface is not a cutter contact point but a curve, Bohez et al. [2] discussed the errors introduced during 5-axis machining which are higher than the intrinsic repeatability of the machine tool. Author has shown the possibility to identify such systematic errors and compensate for them achieving higher performance. *A group of systematic errors can be compensated for directly in the inverse kinematics equations.* Other systematic errors can be combined and compensated for through the total differentials of the inverse kinematics relations. Bohez et al. [2][3] discussed a CAM algorithm for determining the correction for ruled surface 5 axis milling operation. Suh

and Lee [6] in their paper measured the machine errors using a ball-bar in a contouring test and then incorporated them into the CAM to optimize the toolpath accuracy. Ramesh et al. [9] reviewed the sources of errors and the methods to eliminate errors through error compensation for machine tools. The review like the past methods focuses on the error measurements and compensation but not on modeling. Sartori and Zhang [10] classify the methods for geometric measurement as direct and self-calibration based on applied standards. One important reference in this regard is the combination of the individual errors in the total error in Shen and Duffie [11]. For a case 3-axis machine, the vector of geometric errors presented is independent of the machine structure. Soons et al. [12] present a general model of a multi-axis machine complemented by type dependent model of static errors in the relative location of the reference frames in it. The former error model is based on the direct kinematics of the tool and workpiece kinematics' chain where in the translational and angular errors for each link are introduced as an additional transformation. Algorithm developed by Murty et al. [8], cannot be used because the drill was constrained to rotate in a vertical plane.

In this paper the authors are focused on compound angle machining on a part such as a Cylinder Head is loaded with reference to one set of axes, turned about another axis by a specified angle with reference to a different axes system, and then finally, the hole is drilled by a drill tool with unrestricted orientation in space with reference to yet another axes system. The objective is to develop an algorithm to compensate for part-loading errors compounded by these kinematic motions of the part and tool. The algorithm's correctness shall be verified for an example problem on Solid Works, a commercial 3-D solid modeler. The results shall be discussed at the end.

2 FORMULATION OF COMPENSATION ALGORITHM

2.1 PROBLEM STATEMENT AND ASSUMPTIONS

Top center of the movable index table is considered as the reference origin of the (ZXY) coordinate system with reference to which all the position coordinates are designated. B -axis is the vertical axis attached to the index table, which coincides with the spindle Y -axis in the part machining position. As illustrated in Figure 2 a sample block representative of a part is laid on an index table, confined within a fixture with reference to the described (ZXY) coordinate axes system, and subject to some translation and rotation errors. Our intent is to find the corrected movements of the CNC axes so that a correct compound-angle is generated. Here, at this stage of development of the compound-angle problem we assume for simplicity that the block is held perfectly against the XB -plane of the rigid reference surface of fixture. This is true in actual machining operation carried out in the industry. Note that at the part loading position the rotation degree of freedom of the block is *unconstrained* about the Z -direction but it is constrained about X and Y directions and hence there can be no rotation errors about

X and Y directions. Likewise translation errors are constrained in Z -direction but they are unconstrained in X and Y directions. These are depicted in Figure 3.

The major difficulty associated with part-loading is that such errors are very difficult to eliminate due to irregular part configuration and human intervention. In the current strategy, as shown in Figure 2, the part is loaded only once in its position to the best of the operator's ability minimizing the errors. The translation errors and skew error are measured by probing the locating holes at fixed positions placed at C and D with reference to the part location. The effect of these part-loading errors on accuracy of the compound-angle is determined to mathematical accuracy using forward and inverse kinematics and the corrected machine axes movements are formed with the help of the algorithm. The correction algorithm is then loaded into the CNC machine controller to impart corrected movements to the machine axes as a function of the measured errors and other known initial parameters. This method is preferred by many and gains popularity in that less human interruption is involved. However, it demands much more skill on the part of the operator in accurately implementing the algorithm with due regard to the sign convention and sequence of operations as explained in subsequent paragraphs.

We first look at the mathematical statement of the problem posed in Figure 2, which shows the schematic of a part loaded in any position in a fixture on an index table.

In an actual compound-angle machining operation with the part accurately loaded into the fixture, the index table is rotated by a specified angle I about the index table B - axis and then the hole is drilled using the drill at the desired inclination T in the XW -plane and S in the WY -plane. In this situation, the compound-hole axis PQ would be perfect or true. However, as depicted in a blown up picture of the part in Figure 2 the presence of part-loading errors shifts the compound-hole axis from its true position P_iQ_i to a faulty position P_fQ_f . Note that in both the cases the compound-hole axis remains straight and there is no curvature. Thus for the purposes of an error compensation algorithm the problem reduces to giving the required transformations to the faulty axis in space to make it collinear with the true axis in space. This is because linear movement of the drill tool along the spindle axis can account for collinear separation between the true and faulty axes along the tool movement.

2.2 PART LOADING ERRORS AND COMPENSATION SCHEME

There are three issues to consider. First, the translation and rotational errors at the part loading position are unavoidable in any machining operation. Second, although it is possible to superimpose the effects of these errors on the accuracy of the compound angle, what complicates the problem is that these errors are invariably measured with reference to a different datum. So all the errors and the compensation scheme are required to be transformed with reference to a single (XWY) coordinate axes system. Rotation of the index table, rotation of the spindle axis and three linear motions of the location of the

spindle axis are available for correction measures and these are considered sufficient. Figure 3 shows a schematic of the possible part-loading errors, which are translation errors in W and Y direction Δ_w and Δ_y , and rotation error or skew angle (θ) about X -direction. As shown in Figure 4, the location of the idealized hole from index table B -axis origin is marked (P_{0x}, P_{0w}, P_{0y}) and the skew (rotational) error θ is considered occurring about the locating hole B_6 . The transitional errors Δ_w , Δ_y , are measured by probing locating holes C and D and skew error θ is measured about locating hole D shown in Figure 2. To develop an error compensation mechanism, it is necessary to determine the direction cosines of the true axis and the faulty axis in space.

2.2.1 Direction Cosines of true axis

To determine the direction cosines of the true axis in space, first it is necessary to determine the position coordinates of the points where the axis intersects the top and bottom centers of the hole on the part. We begin with 0th position where the top center and bottom center of an imaginary vertical hole are defined as P_0 and Q_0 . To drill an idealized hole, the part is rotated by an angle I about the index table B -axis and then the part is translated by $-S_z$ along negative Z -direction. These two movements would not alter the position coordinates of the top center and bottom center of the hole on the part, which are now defined as P_1 and Q_1 . This is designated as the 1st position. In the next operation, the spindle axis is rotated at an angle T in the ZX -plane and by S in the XY -plane and the drill bit is placed at the top center of the hole P_2 and the drilling operation is completed. If there were no part loading errors, then the drill would exit from the true point Q_2 located on the part so that the true hole-axis P_2Q_2 is formed in its 2nd position. From the known position coordinates of top center of the hole and the spindle rotation angle T and S , using forward transformation matrices, the position coordinates of the point Q_2 on the part at which the drill exits is determined. From this, the direction cosines of the true axis P_2Q_2 are determined. Note here that the expressions for the direction cosines of the true axis would include terms that contain known parameters I , T , S_x , and S but part loading errors do not appear.

2.2.2 Direction Cosines of faulty axis

To determine the direction cosines of the faulty axis in space, first it is necessary to determine the position coordinates of the points where the faulty axis intersects the top and bottom centers of the hole on the part. This is a tricky situation and it is not possible to follow the procedure followed for the true axis straight away. Since the errors occur at the part loading position, first it is necessary to determine the true position coordinates of the exit point of the true axis at the part loading position. For this, the true axis P_2Q_2 is, rotated by an angle $-I$ about

the index table B -axis. Inverse transformation matrices are used to determine the new position coordinates of the point Q_3 to which the point Q_2 on the true axis would move consequent to this reverse motion. However, these motions would not alter the position coordinates of the top center of the hole and so the coordinates of point P_3 would remain the same as P_2 . At this point with the new points on the axis of the hole at the part loading position would be,

$$P_3 = (P_{2z} + \Delta z_{zPI-}, P_{2x} + \Delta x_{xPI-}, P_{2y}) \quad (1)$$

$$Q_3 = (Q_{2z} + \Delta z_{zPI-}, Q_{2x} + \Delta x_{xPI-}, Q_{2y}) \quad (2)$$

Here Δz_{zPI-} , Δx_{xPI-} , etc. show incremental changes to the coordinates of point P_2 and Q_2 due to rotation by an angle I in the negative direction. This would mean that at the part loading position, the true axis is represented by P_3Q_3 . Now we progressively consider the effect of part loading errors on the coordinates of top and bottom centers of the compound hole to determine the position coordinates of the faulty axis. At this point with the consideration of translation errors, the new points on the axis of the hole at the part loading position would be,

$$P_4 = (P_{3z}, P_{3x} + \Delta x, P_{3y} + \Delta y) \quad (3)$$

$$Q_4 = (Q_{3z}, Q_{3x} + \Delta x, Q_{3y} + \Delta y) \quad (4)$$

Now, forward transformation matrices are used to consider effect of the skew error θ about the probe B_6 to give:

$$P_5 = (P_{4z}, P_{4x} + \Delta x_{P\theta}, P_{4y} + \Delta y_{P\theta}) \quad (5)$$

$$Q_5 = (Q_{4z}, Q_{4x} + \Delta x_{Q\theta}, Q_{4y} + \Delta y_{Q\theta}) \quad (6)$$

These are the new position coordinates of the top and bottom centers of the hole. Note in this regard that both Y -coordinate of the probe D_y and Y -coordinate of the true hole P_y will contribute to this change in coordinates. Next, forward transformation matrices are used to determine the new position coordinates of the faulty hole axis as,

$$P_6 = (P_{5z} + \Delta z_{PI}, P_{5x} + \Delta x_{PI}, P_{5y}) \quad (7)$$

$$Q_6 = (Q_{5z} + \Delta z_{QI}, Q_{5x} + \Delta x_{QI}, Q_{5y}) \quad (8)$$

Mathematically stated these two points represent the position coordinates of the faulty axis. If this faulty axis were to be collinear with the true axis then their direction cosines must be the same in all the planes ZX , XY , and YZ . Further, if two lines in space are parallel in two planes, they shall also be parallel in the third plane because the sum of squares of the direction cosines is always equal to unity. Thereafter only linear axes movements will be required to make the true and faulty axes coincident.

2.2.3 Determine Δ_I in ZX -Plane

We first attempt to align the two axes in ZX plane by equating the inclination of lines P_2Q_2 and P_6Q_6 . The inclinations of the true and faulty axes in ZX -plane are determined as follows. This would require the faulty axis to be rotated by an incremental angle about B -axis and that after trigonometric transformations would yield the

following result. Simplified expression for Δ_I is given at the end.

$$P_2Q_{2zx} = a \tan\left(\frac{P_{2z} - Q_{2z}}{P_{2x} - Q_{2x}}\right) \quad (9)$$

$$P_6Q_{6zx} = a \tan\left(\frac{P_{6z} - Q_{6z}}{P_{6x} - Q_{6x}}\right) \quad (10)$$

$$\Delta_I = a \tan\left(\frac{(P_{6x} - Q_{6x}) \times \left(\frac{P_{2z} - Q_{2z}}{P_{2x} - Q_{2x}}\right) - (P_{6z} - Q_{6z})}{(P_{6z} - Q_{6z}) \times \left(\frac{P_{2z} - Q_{2z}}{P_{2x} - Q_{2x}}\right) - (P_{6x} - Q_{6x})}\right) \quad (11)$$

Consequent upon rotating the faulty axis by this incremental angle, the true and faulty axes are made collinear in the ZX plane but this operation would alter z and x coordinates of the top and bottom centers of the faulty axis. The new coordinates of the top and bottom centers of the faulty axis are determined by using forward transformation matrices and are found to be:

$$P_7 = (P_{6z} + \Delta z_{P\Delta_I}, P_{6x} + \Delta x_{P\Delta_I}, P_{6y}) \quad (12)$$

$$Q_7 = (Q_{6z} + \Delta z_{Q\Delta_I}, Q_{6x} + \Delta x_{Q\Delta_I}, Q_{6y}) \quad (13)$$

2.2.4 Determine Δ_S XY -Plane

We then attempt to align the two axes in XY -plane by equating the inclination of lines P_2Q_2 and P_7Q_7 . The inclinations of the true and faulty axes in XY -plane are determined as follows. This would require the faulty axis to be rotated by an incremental angle about S -axis and that is given by the following expression. Simplified expression for Δ_S is given at the end such that true tool inclination is $S' = S + \Delta_S$.

$$P_2Q_{2xy} = a \tan\left(\frac{P_{2y} - Q_{2y}}{P_{2x} - Q_{2x}}\right) \quad (14)$$

$$P_7Q_{7xy} = a \tan\left(\frac{P_{7y} - Q_{7y}}{P_{7x} - Q_{7x}}\right) \quad (15)$$

$$\Delta_S = a \tan\left(\frac{(P_{7x} - Q_{7x}) \times \left(\frac{P_{2y} - Q_{2y}}{P_{2x} - Q_{2x}}\right) - (P_{7y} - Q_{7y})}{(P_{7y} - Q_{7y}) \times \left(\frac{P_{2y} - Q_{2y}}{P_{2x} - Q_{2x}}\right) - (P_{7x} - Q_{7x})}\right) \quad (16)$$

2.2.5 Determine (S'_z, S'_x, S'_y) to position the tool on the part to drill the hole.

In the previous step we determined the true inclination of the spindle axis. We shall now determine the position coordinates of the top center of the hole at which the tool must be positioned to drill the correct hole. For this purpose we start from the position coordinates of the top center of the hole with part loading errors $P_5 = (P_{5z}, P_{5x}, P_{5y})$. Since the part is now being rotated by I' , we determine the new displaced top center of the hole. $P_8 = (P_{8z} = P_{5z}, P_{8x} = P_{5x}, P_{8y} = P_{5y})$ and then $P_9 = (P_{9z}, P_{9x}, P_{9y})$ resulting from using forward transformation matrices with an angle of $I' = I + \Delta_I$. This will give us the true coordinates of the top center of the

hole at which the tool needs to be positioned. This is to be considered in both ZX , and XY planes separately.

2.2.6 Mathematical check

Check the correctness of the Y' and X' thus computed by checking the angle formed by the line P_9Q_7 in XY -plane a which must be the same as S' and in ZX -plane which must be the same as angle T which is proved by expressions on MathCAD file. Note that the variables used in Mathcad are: (X,W,Y) as against our coordinate system of (Z,X,Y) and so the expressions shown are different.

In the expressions below, w-coordinate should be read As x-coordinate in our coordinate system and x-coordinate should be read as z-coordinate in our coordinate system in this paper.

$$\text{atan}\left(\frac{\text{NewP9y} - \text{NewQ7y}}{\text{NewP9w} - \text{NewQ7w}}\right) = 20.186884\text{deg}$$

This is correct.

$$\text{atan}\left(\frac{\text{NewP9y} - \text{NewQ7y}}{\text{NewP9w} - \text{NewQ7w}}\right) = 0.352328\text{rad}$$

This is correct

$$\text{atan}\left(\frac{\text{NewP9x} - \text{NewQ7x}}{\text{NewP9w} - \text{NewQ7w}}\right) = 40\text{deg}$$

This is correct

$$\text{atan}\left(\frac{\text{NewP9x} - \text{NewQ7x}}{\text{NewP9w} - \text{NewQ7w}}\right) = 0.698132\text{rad}$$

This is correct

$$\text{atan}\left(\frac{\text{NewP9x} - \text{NewQ7x}}{\text{NewP9y} - \text{NewQ7y}}\right) = 66.33839\text{deg}$$

(18)

2.2.7 Determine (S''_z, S''_x, S''_y) with the lengths of spindle L_S and tool L_T

And last, the effect of the gage length and tool length is schematically described in Figure 5. Obviously as expected these parameters only affect the correction in X and Y -directions. Now we consider the position coordinates of the spindle axis and the lengths of the spindle and tool to derive final expressions for the new spindle axis location (S''_z, S''_x, S''_y) as follows.

$$S''_z = S'_z \quad (19)$$

$$S''_x = S'_x + (L_S + L_T) \times \cos(S') \quad (20)$$

$$S''_y = S'_y + (L_S + L_T) \times \sin(S') \quad (21)$$

3 EXPRESSIONS FOR A GENERAL CASE WHERE TOOL MOTION IS UNCONSTRAINED IN SPACE

3.1.1 Incremental equations

The following incremental equations are derived for various parameters.

$$\Delta_I = \arctan \left(\frac{(1 - \cos(\theta)) \cos(I + T) + \sin(\theta) \cos(T) \tan(S)}{\sin(I + T) + \cot(I + T) \cos(\theta) \cos(I + T) - \sin(\theta) \cos(T) \tan(S) \cot(I + T)} \right) \quad (22)$$

$$\Delta_S = \arctan$$

$$\left(\frac{\sin(\theta) \cos(I + T) + \cos(\theta) \tan(S) \cos(T)}{\cos(I) (\cos(\theta) - 1) \cos(I + \Delta_I + T) + \cos(\theta) \sin(T) \sin(\Delta_I) + \cos(T) \cos(\Delta_I) - \cos(T) \sin(\theta) \tan(S) \cos(I + \Delta_I)} \right) - S \quad (23)$$

$$\Delta S_z = (S_z'' - S_z) \quad (24)$$

$$\Delta S_x = (S_x'' - S_x) \quad (25)$$

$$\Delta S_y = (S_y'' - S_y) \quad (26)$$

3.1.2 Absolute equations

Absolute equations as given below are determined by algebraically adding the incremental corrections to the correct values without part loading errors. Eventually, the machine controller will impart these movements to the machine axes to arrive at the true axis for the compound hole. After simplification, the absolute equations in terms of the known parameters are as follows.

$$I' = I + \Delta_I \quad (27)$$

$$S' = S + \Delta_S \quad (28)$$

$$S_z'' = \left(\begin{aligned} &\sin(I + \Delta_I) [-D_x (1 - \cos(\theta) - (P_{0x} + \Delta_x) \cos(\theta) + (P_{0y} + \Delta_y - D_y) \sin(\theta) + (P_{0z}) \cot(I + \Delta_I))] \end{aligned} \right) \quad (29)$$

$$S_x'' = \left(\begin{aligned} &\cos(I + \Delta_I) [D_x (1 - \cos(\theta) + (P_{0x} + \Delta_x) \cos(\theta) - (P_{0y} + \Delta_y - D_y) \sin(\theta) + (P_{0x}) \tan(I + \Delta_I)] \\ &(L_S + L_T) \cos(S') \end{aligned} \right) + \quad (30)$$

$$S_y'' = \left(\begin{aligned} &D_y (1 - \cos(\theta) + (P_{0y} + \Delta_y) \cos(\theta) + (P_{0x} + \Delta_x - D_x) \sin(\theta) \\ &+ (L_S + L_T) \sin(S') \end{aligned} \right) \quad (31)$$

3.1.3 Sign convention for angular corrections

The skew angle error θ may be in either direction. Further, the expressions for Δ_I and Δ_S , given in Eq. (22) and Eq. (23) may result in positive or negative numbers. If the skew error is counter clockwise, then θ is considered

negative. If expression for Δ_I is positive then index table is incremented in the counter clockwise direction by this amount. If Δ_S is found positive then the spindle axis rotation is incremented by this amount in the counter clockwise direction.

4 COMPENSATION ALGORITHM WHERE TOOL MOTION IS UNCONSTRAINED IN SPACE

Transformation equations are used in conjunction with input variables that become input values upon use. The following lists the steps required in computing the final solution. It is essential to follow the following steps in the proper order with proper regard to the sign convention while feeding the algorithm to the machine controller and if not done so, the results will go wrong.

- Compute Δ_I using the input data and *incremental offset equation* for Δ_I .
- Compute Δ_S using the input data, Δ_I computed in (1) above and *incremental offset equation* for Δ_S .
- Compute S' using the input data and Δ_I computed in (1) and *absolute offset equation* for S' .
- Compute S_z'' , S_x'' , and S_y'' , using the input data, Δ_I , and S' computed in (1), and (3) above, and *absolute offset equations* for S_z'' , S_x'' , and S_y'' .
- Compute ΔS_z , ΔS_x , and ΔS_y , using the input data, S_z'' , S_x'' , and S_y'' , computed in (4) above, and *incremental offset equations* for ΔS_z , ΔS_x , and ΔS_y .

Note: The steps are required to be followed in the proper order because expression for Δ_S contains Δ_I which must be determined first. This has occurred because true and faulty axes were made parallel in ZX - plane first. It is also possible to first equate the angles in XY -plane and in that case expression for Δ_I will contain the term of Δ_S , which will have to be determined first with a different set of equations.

5 VERIFICATION OF ALGORITHM

In the absence of a specific part, the algorithm is verified using CAD tool.

5.1 EXAMPLE 1

5.1.1 Input parameters for the compound hole

The position coordinates of the top center of the true hole are $P_{0z} = 254$ mm, $P_{0x} = 355.6$ mm, and $P_{0y} = 304.8$ mm. Based on past experience and for the 2-D case, the part loading errors are assumed to be $\Delta_x = 0.230607$ mm, $\Delta_y = -0.226616$ mm, and skew error $\theta = -0.16018$ deg.

5.1.2 Assumed known parameters

The position coordinates of the locating hole are $D_z = 25.4$ mm, $D_x = 159.5501$ mm, and $D_y = 127$ mm. The spindle

rotation angle is $S = 20 \text{ deg}$, $T = 40 \text{ deg}$. The index table rotation is $I = -(180 \text{ deg} + 20 \text{ deg})$. Position coordinates of the spindle axis are $S_z = -254 \text{ mm}$, $S_x = -304.8 \text{ mm}$, $S_y = 203.2 \text{ mm}$.

5.1.3 Output from Mathcad Numerical Tool (Figure 6)

In the following the results as obtained in Mathcad program are reproduced below.

Coordinate System: (XY)

NewP7x = -14.19237m NewP7w = -9.766167m

NewP7x = -360.486202mm NewP7w = -248.06065mm

NewP7y = 11.969449m

NewP7y = 304.02399mm

Angle Δ_I is Newlincremental on Mathcad program

Newlincremental = 0.015357deg

Newlincremental = $2.680305 \times 10^{-4} \text{ rad}$

5.1.4 Output from CAD (Solid Works) Tool

Value of $\Delta_I = 0.01535 \text{ deg}$ See Figure 9 for print out.

Coordinate system: (ZXY)

$P_{7z} = -360.48356 \text{ mm}$

$P_{7x} = -248.05659 \text{ mm}$ See Figure 10 for print out.

$P_{7y} = 304.02 \text{ mm}$

Note that the variables on Mathcad file are different. from the Solid modeler coordinate system.

6 CONCLUSION

In this paper we have developed a 'Compensation Algorithm' to solve compound-angle machining problems involving parts such as Cylinder Head with translation and rotation part-loading errors and where the tool motion is unconstrained in space. It is shown that mathematical approach to the solution provided the required compensation algorithm with no human intervention irrespective of the magnitude and quality of the translation and rotation errors. Both forward and inverse transformation matrices are used to determine the direction cosines of the true and faulty axes in space. Finally an algorithm to calculate new positions of machine axes is developed to take into account transitional and rotational errors at the part loading position. The transitional errors are considered in the X and Y directions by probing locating holes C and D , while the skew (rotational) error θ is considered to occur about the locating hole D . Both absolute and incremental solutions are derived. In the incremental solution, the machine is

positioned to the point where machining should occur without errors, and then incremental adjustments are made from this idealized point. Two rotary axes, S (Spindle body) and I (Rotary Index Table), are adjusted as well as three linear axes: Z , X , and Y . The top center of the table is taken as the origin. The algorithm also takes into account the gage length of spindle and length of tools itself that also affect the positioning of the axes and tool tip. Sign convention and proper order of the steps is important. Correctness of the algorithm has been verified using Solid Works, a commercially available 3-D solid modeler. The results are found accurate. It is shown that the compensation algorithm is accurate as well as efficient.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

P_{0z} = Distance from Index Table B -axis origin to the idealized hole in the Z -direction (Figure 4)

P_{0x} = Distance from Index Table B -axis origin to the idealized hole in the X -direction (Figure 4)

P_{0y} = Distance from Index Table B -axis origin to the idealized hole in the Y -direction (Figure 4)

D_x = Distance from Index Table B -axis origin to the D probe in the X -direction (Figure 4)

D_y = Distance from Index Table B -axis origin to the D probe in the Y -direction (Figure 4)

I = Angle of rotation of the Index Table B -axis to produce idealized hole (Figure 4)

S_z = Distance from Index Table B -axis origin to the spindle axis in the Z -direction for idealized hole (Figure 5)

S_x = Distance from Index Table B -axis origin to the spindle axis in the X -direction for idealized hole (Figure 5)

S_y = Distance from Index Table B -axis origin to the spindle axis in the Y -direction for idealized hole (Figure 5)

S = Angle of rotation of the spindle about an axis parallel to X -axis about spindle location to produce idealized hole (Figure 5)

T = Angle of rotation of the spindle about an axis parallel to Y -axis about spindle location to produce idealized hole (Figure 5)

L_s = Spindle Length (Figure 5)

L_T = Tool Length (Figure 5)

Δ_x = Part loading translation error for the top center of the compound hole in X -direction measured probing locating holes C and D (Figure 2 and Figure 3)

Δ_y = Part loading translation error for the top center of the compound hole in Y -direction measured probing locating holes C and D (Figure 2 and Figure 3)

θ = Part loading rotational error about X -direction measured about locating hole D (Figure 5)

d = Depth of the hole in Y -direction (Used only to develop the algorithm but it is not a part of the algorithm.)