Machine Tool Accuracy Quick Check in Automotive Tool and Die Manufacturing

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Abstract
A process to quickly check large CNC milling machine accuracy in the automotive tool and die manufacturing has been developed using a thermally and geometrically stable light weight artifact (tetrahedron) [1]. In the process described, within a half an hour the artifact is inspected, data analyzed and information provided to indicate if the machine axes position and squareness are acceptable. The analysis software used is integrated to the system to provide user friendly artificial intelligent decision making (INORA SRS™). The software output is in the form of a simple chart indicating to the operator if his machine is dimensionally acceptable before the beginning of the next job. The process is currently implemented within GM and has been used, for over a year in monitoring machine dimensional stability.

Keywords:
Machine accuracy, Artifact, Tetrahedron, Automotive dies, Affine Transformation, Touch Probing, Sphere Fitting

1 INTRODUCTION

When developing a new automobile, the die construction process for major body panels requires a large amount of time. This process is composed of several steps, including die design, pattern development, casting, construction and tryout. The construction portion is the most expensive and takes the longest time [2]. The machining of these large dies can take up to several weeks to complete and is done using large CNC milling machines with several meters long axes of travel. To be able to produce die components true to the original die design data, the machining department requires that the milling machine be highly accurate and of a stable geometry. Errors due to machining will impact not only the die assembly but also the ability for the die to make acceptable panels in tryout. Any dimensional error found during the assembly or tryout of these dies will delay the delivery to production of the complete die set by several days, if not weeks. When an error is found, the construction is interrupted, and a lengthy process of root cause analysis and identification is started. To avoid delays due to process errors, die components are precisely machined for the final assembly with minimum hand finishing or hand fitting. The "machine and assemble" approach helps reduce manufacturing cost and provides the necessary quality with a minimal Time-In-System.

A robust and dimensionally stable part-to-part machining system is required to support the "machine and assemble" approach.

In automotive die manufacturing, controlling the process via 100% inspection of all parts is costly and with limited impact to the quality of next part. Dies are inherently different from each other. To manufacture a vehicle product, only one type of die is needed in each die line. Even though a line of dies contains several dies, each one is used to accomplish a different operation: blanking, forming, trimming…, etc.

This paper describes a low investment method capable of providing a robust machining process monitoring in automotive die manufacturing. The method, as implemented, has also the advantage of providing important information about detrimental machine activity such as crashes or damages due to either operator or programming errors.

2 VARIABILITY IN DIE MANUFACTURING

2.1 Error Budget

As in any other manufacturing process, die construction requires means to identify manufacturing errors along the process, from programming, to assembly of components [3]. Since each die is a one of kind component, the approach to machining is variable and hence can be cause to a large amount of manufacturing errors. The programmer and machine operator see each die as a new die, with often major differences from the previous one and therefore with its own challenges and learning.

In fact, when we monitored the time spent for error correction during the die construction process, we were able to show that errors due to machining required 50% of the total time it took to correct all errors (CAM: 23%; Pattern: 13%; Initial Machining: 16%; Blocking: 9%; Final Machining: 34% and Final Assembly: 5%).

A large portion of the machining errors are due to variations in machine geometry. For example, the out of squareness between two guide pads at each extremity of the die shoe (up to 4 meters away) and the bottom surface is shown to be directly related to the out of squareness between machine axes. Also, the location of the guide pins on the die outside edge, correlates well to the machine axis position accuracy and repeatability. Both of these features are used to precisely align the top and the bottom die halves, while in the press making several thousands of parts at high production rates.

In GM internal large machine tool studies [3] [4], the error budget was identified to be distributed as follows: static: 49%; dynamic: 27%; environment: 17%; measurement tools: 5% and 2% due to cutter deflection.

From these studies, we also determined that 65% of the static error is due to axes positioning and squareness errors. Monitoring the machine positioning and squareness would therefore give us the ability to reduce appreciably the impact of machining errors.

2.2 Concept proposed

The initial approach to machine dimensional stability is first to calibrate the machines regularly and second to maintain a stable shop environment to minimize the thermal affect. In a production environment, machines are regularly calibrated. However, in a large automotive metal fabrication plant, controlling the environment is cost prohibiting. Once the machines are calibrated it is more economical to devise a mean to quickly and regularly check few parameters which are good indicator of machine geometry changes.

A tetrahedron shaped artefact from INORA Technologies was selected for this application (INORA Patent No. US 6,836,323, B2).

Figure 1: The INORA Tetrahedron on a machine table

3 QUICK CHECK PROCESS VALIDATION

3.1 Assessment of Geometric Errors

The use of laser interferometer is the most common technique to fully assess machine tool geometric errors. This method is accurate and can be used to determine all the translation and angular errors. Unfortunately, the method is time consuming and requires highly skilled personnel to run. The Telescoping Magnetic Ball Bar (TMBB) test [8] is a quick and easy to use diagnostic tool to evaluate machine errors. The TMBB test as well as other variance of the telescoping ball bar that are available today in the market, are best suited for assessing machine dynamic errors [5][12].

The machine quick check process described in this paper is a new technique utilizing a Spatial Reference System (INORA SRS™) [1]. The SRS is a calibrated tetrahedron artefact constructed from six carbon-fiber bars, each with a magnetic end cap that connects to a sphere. The bars have a low coefficient of thermal expansion (0.1μm/m/ºC) to minimize the temperature effects.

The quick check process is performed in three easy steps by the machine operator. The first step is setting the artefact on the machine table. The second step is running a part probing program to collect data on the four spheres. The third step involves running INORA SRS data analysis software. In less than half an hour, the operator is provided with an evaluation on his machine positioning and squareness.

3.2 Setup and Probing

The SRS tetrahedron can be setup in any orientation on the table. For the sole purpose of automated probing, it is best to align one of the sides of the artefact along one of the main machine axes (X or Y in our case). When repeating the test, it is recommended to setup the artefact, in about the same location on the machine table. The mounting system is designed to fit into the machine T-slots for quick setup.

The part program uses trilateration technique to locate the four sphere centres [7] [8]. Assuming the sphere centres are $P_1(0,0,0)$, $P_2(L_4,0,0)$, $P_3(X_3, Y_3,0)$ and $P_4(X_4, Y_4, Z_4)$ and the six sides of the SRS tetrahedron are L_1, L_2, L_3, L_4, L_5, and L_6, all unknown coordinates are calculated using the following formulations:

$$X_3 = \frac{L_5^2 - L_6^2 + L_4^2}{2L_4}; \quad Y_3 = \sqrt{L_5^2 - X_3^2}; \quad X_4 = \frac{L_1^2 - L_2^2 + L_4^2}{2L_4}$$

$$Y_4 = \frac{L_1^2 - L_3^2 + L_5^2 - 2X_3X_4}{2Y_3}$$

$$Z_4 = \sqrt{L_1^2 - X_4^2 - Y_4^2}$$

The initial portion of the part program contains a probing routine to find the centre of the top sphere which is preset to $P_4(X_4, Y_4, Z_4)$. Then 20 points distributed over the upper part of the sphere are measured and recorded. The same process is repeated for the remaining spheres. In the case of calibrated spheres, collecting 20 data points is sufficient for the sphere fitting computation [9]. Probing data is stored in a file on a PC connected to the machine CNC via RS-232 or Fanuc High Speed Serial Bus (HSSB) using a routine developed by General Motors. The data file is then imported to the INORA SRS software for final analysis.

Care must be taken to minimize probing errors. Since 3D probing is required, the touch probe being used for the measurements should have a 3D error compensation map in the CNC, especially if the touch probe has a mechanical kinematics design [10]. Renishaw recommended using a strain gauge touch probe (MP700) for sphere fitting applications.

3.3 Data Analysis

In the final product, the data collected is analyzed using INORA software algorithm described later in this paper. However, to validate the commercial software output we did the initial analysis using basic math tools. We applied sphere fitting techniques to the probe data to find the location of the four sphere centres. The result is then used to determine the tetrahedron bar lengths. Figure 2 shows a pictorial of the analysis results: a distorted tetrahedron made using the measured data super-imposed over the calibrated artefact. The difference in the shapes is caused by errors in the machine geometry. Quantifying these errors requires finding the parameters of the matrix representing the transformation of the artefact to the measured tetrahedron distortions.

3.4 Sphere Fitting

An important aspect in the validity of this method hinges around how precisely we determine the centres of the four spheres from the probe data. For that purpose, we selected to use the same approach often used in CMM applications [11] to find the least-squares best-fit sphere.

Assuming that we have estimates of the centre (x_0, y_0, z_0) and radius r of the sphere, the Gauss-Newton algorithm provides the final values for these parameters using the following steps:

A. form vector **d** using $d_i = r_i - r$ where :

$$r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$$

B. Form Jacobian matrix J according to:

$$J = \begin{bmatrix} \frac{\partial d_1}{\partial x_0} & \frac{\partial d_1}{\partial y_0} & \frac{\partial d_1}{\partial z_0} & \frac{\partial d_1}{\partial r} \\ \frac{\partial d_2}{\partial x_0} & \frac{\partial d_2}{\partial y_0} & \frac{\partial d_2}{\partial z_0} & \frac{\partial d_2}{\partial r} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial d_n}{\partial x_0} & \frac{\partial d_n}{\partial y_0} & \frac{\partial d_n}{\partial z_0} & \frac{\partial d_n}{\partial r} \end{bmatrix}$$

C. Solve the linear least-square system:

$$J\begin{bmatrix} P_{x_0} \\ P_{y_0} \\ P_{z_0} \\ P_r \end{bmatrix} = -\mathbf{d}$$

D. Update the parameters according to:

$$x_0 = x_0 + P_{x_0} \;;\; y_0 = y_0 + P_{y_0} \;;\; z_0 = z_0 + P_{z_0}$$

$$r = r + P_r$$

E. Repeat these steps until the algorithm has converged.

This least-squares best-fit method is reliable provided that blunders do not exist in the data set. The advantage of using INORA algorithm is that blunders are removed automatically.

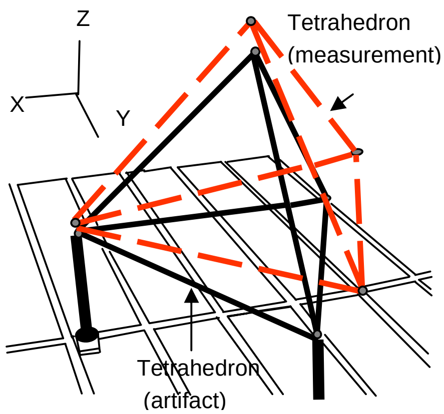

Figure 2: Measured tetrahedron compared to artefact

3.5 Positioning and Squareness Errors Calculation

Test performed per ASME B5.54 [12] indicated that compensated mechanical kinematics type touch probe using a spherical ball may have centre fluctuation less than 3 microns on a typical machining centre. Distortions of the tetrahedron obtained from probe data are the result of machine geometric errors provided that probing errors are minimal. Affine transformation can be used to describe the distortion as follows [13]:

$$[MeasuredCenters] = [AffineTransformation] \times [NominalCenters]$$

$$\begin{bmatrix} x_1' & x_2' & x_3' & x_4' \\ y_1' & y_2' & y_3' & y_4' \\ z_1' & z_2' & z_3' & z_4' \\ 1 & 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \\ y_1 & y_2 & y_3 & y_4 \\ z_1 & z_2 & z_3 & z_4 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

The 12 parameters in the affine transformation matrix which represent 3 translations, 3 rotations, 3 scales and 3 shears can be solved using least squared method. The 3 translations are m_{14}, m_{24} and m_{34} while rotations, scales, and shears are encoded in the upper 3x3 portion of the matrix.

Scaling in X, Y, and Z directions are magnitudes of the vectors of the upper 3X3 portion:

$$S_x = \sqrt{m_{11}^2 + m_{21}^2 + m_{31}^2}$$

$$S_y = \sqrt{m_{12}^2 + m_{22}^2 + m_{32}^2}$$

$$Sz = \sqrt{m_{13}^2 + m_{23}^2 + m_{33}^2}$$

Shearing in XY, XZ, and YZ planes can be determined by finding the dot product between the vectors of the upper 3X3 portion:

$$Zxy = \left(\frac{m_{11}\hat{u} + m_{21}\hat{v} + m_{31}\hat{w}}{S_x}\right) \bullet \left(\frac{m_{12}\hat{u} + m_{22}\hat{v} + m_{32}\hat{w}}{S_y}\right)$$

$$Zxz = \left(\frac{m_{11}\hat{u} + m_{21}\hat{v} + m_{31}\hat{w}}{S_x}\right) \bullet \left(\frac{m_{13}\hat{u} + m_{23}\hat{v} + m_{33}\hat{w}}{S_z}\right)$$

$$Zyz = \left(\frac{m_{12}\hat{u} + m_{22}\hat{v} + m_{32}\hat{w}}{S_y}\right) \bullet \left(\frac{m_{13}\hat{u} + m_{23}\hat{v} + m_{33}\hat{w}}{S_z}\right)$$

The scaling effect is due to measurement system error, ball screw pitch error or thermal expansion of the machine and causes positioning errors. The shearing effect is a result of the machine axes not being perpendicular and cause of squareness errors. If the machine is assumed to be a rigid body, the following Homogeneous Transformation (HTM) matrices describe independent movements of X, Y and Z axes and their relative positioning and squareness errors. The HTM matrices are derived using equations found in [14]:

$${}^{X}T_{X'} = \begin{bmatrix} 1 & 0 & 0 & X - X \cdot S_x \\ 0 & 1 & 0 & -X \cdot Z_{xy} \\ 0 & 0 & 1 & -X \cdot Z_{xz} \\ 0 & 0 & 0 & 1 \end{bmatrix} ; \quad {}^{Y}T_{Y'} = \begin{bmatrix} 1 & 0 & 0 & -Y \cdot Z_{xy} \\ 0 & 1 & 0 & Y - Y \cdot S_{xy} \\ 0 & 0 & 1 & -Y \cdot Z_{yz} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^{Z}T_{Z'} = \begin{bmatrix} 1 & 0 & 0 & Z \cdot Z_{xz} \\ 0 & 1 & 0 & -Z \cdot Z_{yz} \\ 0 & 0 & 1 & Z - Z \cdot S_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

3.6 Testing Frequency and Sample Results

To validate the process within GM Die and Tool Operations, a procedure was implemented requiring the machine operators to perform the test on monthly basis.

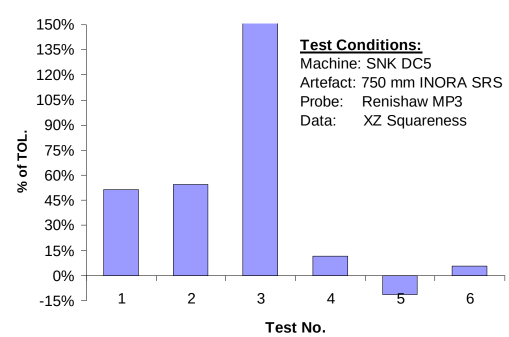

Figure 3: Sample squareness results

In figure 3, the data show clearly an out of tolerance condition in squareness. Probably a major machine crash happened between test #2 and test #3. After test

#3, the machine was recalibrated to bring the squareness within acceptable limits.

4 THE INORA SPATIAL REFERENCE SYSTEM

The INORA SRS™ combines both the strategy of a fast and easy-to-operate artifact with enhanced mathematical decision making and engineering control (Unexpected Deviation Detection - UDD) [15] [16].

4.2 Basic operation principle

If we consider a "simple" 3-axis CNC machine that moves its tool using three pair wise orthogonal axis, the major discrepancies from the target location are due to three cross errors (pair wise axis deviation - orthogonality) and three position errors (axis scales).

The measurements on a calibrated spatial body, such as the tetrahedron, will provide data that are evaluated using affine spatial co-ordinate transformation techniques to determine the orthogonality and scale deviations.

4.2 Mathematical computations

To obtain the above mentioned deviations, all four spheres of the tetrahedron have to be evaluated with a high degree of accuracy. The centres of the spheres represent the corresponding four end points of the tetrahedron and need to be precisely determined. To obtain the exact location of the sphere centres, it is essential that the algorithm used detects and removes all points with "unexpected deviations" from the data collected while measuring the spheres' surfaces. This is the initial, most important first step computation within the INORA SRS algorithm.

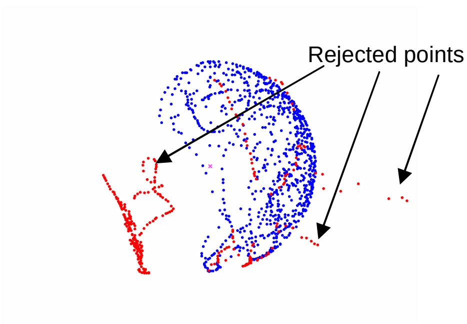

Figure 4: Cloud of points from scans of a sphere

Figure 4 shows a cloud of approximately 2500 points from the output of a laser-tracking device. The INORA SRS algorithm can detect and eliminate automatically some 28% of the points (INORA Breakpoint Law allows up to 50% to be removed) that were determined to have "unexpected deviations" (red points) from further computations.

The following computational step in INORA will use the blue points only to determine the sphere's centre and diameter with accuracy similar to using Least Squares and MinMax techniques together.

Although the mathematical background for INORA SRS algorithm seems simple, the theoretical background for adjustment and optimization is quite sophisticated in theory and computation.

5 CONCLUSION

The work presented in this paper is a further contribution in the area of automotive die manufacturing machining accuracy and lead time reduction. In automotive dies machining, it is more economical to monitor and control the machining system than to monitor and correct defectives parts after they are made. Furthermore, in support of the implementation of "smart machining systems", we believe that machine accuracy inspection and analysis tools need to become an integral part of the machine control diagnostics toolbox.

6 ACKNOWLEDGMENTS

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