Abstract

Machine Capability Studies (MCSs) are used throughout manufacturing industries to help understand the natural variation of machine tools. This paper presents a case study in which a new method was developed for conducting and analyzing a MCS. The new analysis technique uses SAS/GRAPH® GCONTOUR procedure to produce color stereographic projections or "maps" of the variation within test parts. These maps can reveal interactions between machine axes that are otherwise hidden using conventional techniques.

Introduction

The most common methods used for determining a machine's "capability" fall into two categories: Static and Dynamic testing. Static testing uses a positional measuring device (like a laser) to measure the machine's ability to move to various positions within its working envelope. Deviations from the targeted position are recorded and adjustments are made if the deviations exceed the factory specifications.

In contrast, dynamic testing tests the machine's ability to produce parts within given specifications. The parts are measured and a variance is then calculated for each feature of interest. Using SAS/QC® CAPABILITY and SHEWHART procedures, one can create histograms and run charts from the data, and readily calculate capability indices (Cp, Cpk).

A degree of certainty (or uncertainty) can be assigned to the prediction of how the machine will perform over time, providing the process is stable and other statistical criteria are satisfied.

The problem with dynamic testing is that some part configurations do not lend themselves to understanding the machine's behavior. The part may be complex in nature, requiring the machine to move in multiple axes simultaneously (like the X and Y axes). And when it comes time to do the analysis, the features created using both X and Y axes may show a problem, but it cannot be determined what variance component is due to the X axis and which is due to the Y. So, one does not know which axis on the machine needs repairing.
Case Study

The following case study presents a test part, a testing method and an analysis technique which identified a problem with a factory milling machine.

The Test Part

Figure 1 shows the final design for the test part that was used. Machining the spherical top using a spherical cutter (Balnose Endmill) forced the machine to move using all possible axis combinations. Thus, this design lent itself to understanding the machine's behavior by providing measurement points for each of the machine's movements.

The Test Method

In the test, the part's domed top was milled in a spiral manner (Figure 2), starting on the side (Equator), spiraling up to the top (North Pole, the geographical jargon comes from the analysis, which will be covered later). Three test parts were made and inspected using a Coordinate Measuring Machine (CMM). During the inspection the dome surface was probed in 5° increments of Latitude and 10° increments of Longitude. This resulted in 649 measurement points on the surface.

Analysis

Before you can analyze any data, you must first understand what the data represents. The data provided from the CMM was in terms of theoretical vs. actual X, Y and Z coordinates. Since the shape of the part is in theory a perfect hemisphere with a radius of 1.500 inches, a comparison with the actual radius value can be made from the X, Y and Z components. Thus, for any point on the hemisphere's surface, the actual radius, R_a, can be subtracted from the theoretical radius, R_t (= 1.500), obtaining the difference in terms of deviation from nominal. For example, if R_a = 1.498, then 1.498 - 1.500 = -.002 inches (undersize in this case).
The measured points for each part were converted into deviations from nominal, or resultant values, and analyzed using PROC CAPABILITY. Figure 3 is a histogram of deviations from nominal for all three test parts. As shown, the data appear to be skewed and failed several statistical tests of normality. Note: capability indices, like Cpk, should not be calculated for this data since values calculated using the Cpk formula assume normality for the data.

It is difficult, looking at the results so far, to tell exactly what is causing the skewness. Other traditional charting methods were tried, but they also failed to present the data in a manner which could be easily interpreted. The problem is that the part is 3 dimensional and the response variable (deviation from nominal) added a 4th dimension. This is very difficult to represent on a 2 dimensional piece of paper.

The Solution

The solution to this problem came from the unlikely place of the U.S. Geological Survey Dept. (Synder, J.P.). Since the part area being tested was a hemisphere, projection techniques could be used to project this shape onto a flat plane. Contour lines could then be drawn on this map to depict changes in elevation. A Polar Stereographic projection was selected from dozens of different projection methods because it is an equal area projection technique, which is valid for statistical studies.

A polar stereographic projection (Figure 4) is accomplished by constructing a line from the base of the sphere (South Pole) to the point of interest and extending it to the point of intersection with a plane tangent to the top of the sphere (North Pole).

For any point A (Figure 5), the projected position P will have coordinate values on the projection plane (Figure 6) given by:

\[ X = 2R\cdot\sin \left( \frac{\pi - \phi}{4} \right) \sin \lambda \]
\[ Y = 2R \cdot S \cdot \tan \left( \left( \frac{\pi}{4} - \frac{\phi}{2} \right) \cos \lambda \right) \]

Where:
\( \phi \) = Angle of Latitude in radians
\( \lambda \) = Angle of Longitude in radians
\( R \) = Spherical radius
\( S \) = Scaling factor (1=full size)

A program\(^1\) was written using SAS\(^\circledR\) software to transform the raw data into projected data using this formula. The program then generates a contour plot (Figure 7) of the projected data.

It was necessary to use color because two error conditions could exist. In one condition the part could be undersize. Shades of red were used to depict this. The other condition is when the part is oversize. Blue was used to depict this. If the part is to size (nominal) then the plot is white.

(Note: Figure 7 appears in shades of grey since color is not used in the SUGI 19 Proceedings or with the SUGI Copy Service. A color copy of Figure 7 can be obtained by contacting the author.)

On the plot, the very center represents the top of the part, or North Pole. The concentric rings represent lines of latitude, with the outermost ring being the Equator. The coordinate system for the machine is identified to the right of the plot.

The plot shows areas of both undersize and oversize conditions. It shows that the tops of the parts were cut oversize, yet no more than +.003. What stands out though is the area cut undersize in the 3rd quadrant. It happens in an area when both X and Y axis are in motion. This undercut area is what is causing the distribution to be skewed.

Conclusions
The results of this study showed that a problem did exist in the machining of the test parts. The quality of the parts are certainly unacceptable by most standards. Maintenance technicians were able to use the contour plots to identify what needed to be fixed on the machine. In this case, there was a minor imbalance in the machine's control circuitry which had gone undetected during a static test.

The techniques presented in this paper may seem uniquely suited to machine capability studies, but the method for achieving success is not. It came from blending two fields that were previously dichotomous. Such blendings result from overcoming existing paradigms and viewing a problem from a fresh perspective. It is my hope that these techniques help others to view their processes from "another point of view" and perhaps re-evaluate their current methods.

References
N/C Milling Machine Capability Study

Color Stereographic Projection

Average Deviation From Nominal

-0.005 to 0.004
-0.004 to 0.003
-0.003 to 0.002
-0.002 to -0.001
-0.001 to 0.000
0.000 to 0.001
0.001 to 0.002
0.002 to 0.003
0.003 to 0.004
0.004 to 0.005
0.005 to
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\[\text{The program used to create Figure 7 was omitted from this paper due to space restrictions but is available from the author upon request.}\]

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