Journal of Manufacturing Systems xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Assessment and implementation of Global offset compensation method

Jie Gu, John S. Agapiou*

General Motors R&D, 30500 Mound Rd., Warren, MI, 48092, USA

A R T I C L E I N F O

Keywords:
Error compensation
Machine accuracy
Machine part quality
Machine tool compensation

A B S T R A C T

Nowadays, the demand of tighter tolerance components requires more accurate machine tools with volumetric compensation. In mass production, post-machining inspection of the workpiece on a coordinate measuring machine (CMM) of all or just some control features of the parts provides statistical quality control information for all the parts and the variability of the manufacturing process. The paper explains the precision enhancement of machine tools according to Global offset, including parameter error modeling, identification and compensation. The method is utilizing the part quality CMM data to determine the specific compensation parameters that are used in the machine tool controller to minimize the machine tool errors. The aim of this method is to explain the compensation of multiple sources of errors including those affected by the rigid body behavior and the deformation due to dynamic forces, thermos-mechanical changes and backlash (that are repeatable from part-to-part) in a machine tool. Part deformation due to cutting and/or clamping forces that are repeatable can be also compensated. The 3D weighted least square fit is explained to determine the compensation parameters. It makes compensation easy and convenient using part measurement data. Simple scenarios are used to illustrate the capabilities of the Global offset compensation method based on a very simple part.

Introduction

CNC machine tools with high accuracy are utilized in manufacturing for mass production. Volumetric accuracy of machine tools depends on the positional accuracy of the cutting tool in relation to the workpiece that is located in the fixture. Several methodologies have been developed for volumetric calibration of machine tools [1,2]. Some methods are found quite effective for manufacturing high precision components with good dimensional accuracy and reliability. Laser interferometry is a commonly used optical technique with the disadvantage of complexity and time of set-up [1,2]. Lately, the laser tracker or laser tracer are employed for indirect error measurement. A multilateration based scheme is used with the tracking interferometer to describe the volumetric error through a volumetric point cloud. While a laser tracker is more suitable for large size machine tools, the laser tracer, a telescopic scheme, is better for small to medium size machine tools (maximum measuring volumes of 1 m^3), because it is much faster method [1]. Since most of the above equipment for positioning error mapping require trained personnel and several hours to days for evaluating and calibrating the volumetric accuracy of machine tools, volumetric calibration is not often implemented in machine tools at a yearly interval. Therefore, the volumetric compensation is not as accurate as required after the initial setup of a new machine tool without periodic calibrations as it is specified for CMMs (Coordinate Measurement Machines). In addition, the calibration takes place at different thermal and load conditions for the machine compared to machining parts and it mostly compensates for the geometric errors [6–12].

The Global offset compensation method has been successfully implemented for mass production in the automotive industry. It is a fast method as long as the part dimensional measurements are available (i.e. by a CMM) for production control. This method uses very accurate data generated by a CMM [13] and it resembles the on-machine measurement method but it is more accurate because the part is measured by another precision machine (i.e. CMM) [2]. It makes compensation easy and convenient. The general methodology for 4- and 5-axis machines and its comparison to the traditional work offset coordinate systems, available in CNC machines, are discussed in previous papers [3–5].

The comparison of the Global offset with the traditional work offset coordinate systems is discussed in detail in Ref. [3]. The error modeling and compensation model for the 4- and 5-axis machine tools is discussed in detail in References [4,5] respectively. The strategy behind this method is to utilize the geometrical and profile measurement errors of a part that are used for compensating the machining process for identical parts. This new automated compensation method is based on the offline part dimensional measurements in a CMM; it estimates the offsets in the WCS (Work Coordinate System) to compensate the machine tool errors including the fixture and table/pallet errors together with the tool length, some of the dynamic errors due to part clamping,

---

* Corresponding author.
E-mail address: John.agapiou@gm.com (S.A. John).

https://doi.org/10.1016/j.jmsy.2018.04.013
Received 30 November 2017; Received in revised form 27 February 2018; Accepted 15 March 2018

Please cite this article as: Agapiou, J.S., Journal of Manufacturing Systems (2018), https://doi.org/10.1016/j.jmsy.2018.04.013

tool deflections, and average temperature changes in the workspace. The compensation method is based on error correction through software and interfacing the NC program with macro variables without generating new NC Codes. Global offset parameters are stored into the computer for compensation purposes, to continue to run the manufacturing production or batch through compensated codes. This methodology was found quite effective to manufacture components in mass production with better dimensional accuracy. This capability allows newer part designs with high precision and consistent performance.

This paper details the least square fit solver that is part of the compensation software. As will be shown, the least square fit approach can be applied to three-dimensional measurements, and can quickly and accurately calculate CNC work offsets to achieve required part print tolerances. The integration of the compensation algorithm, the transformation of the CMM coordinate frame into WCS and least square fit provides the 3D compensation capability to optimize the part dimensional quality with respect to shape, size, skewness, feature position, and distortion. A further enhancement to the compensation software detailed in this paper is the ability to easily customize the tolerance weight of a given machined feature, to facilitate achieving a good Cpk for all the features.

Overview

Lets consider a 5-axis machine tool with A- and B-rotary tables where the Global offset was analyzed in a previous paper [3]. The Global offset is made up by nine compensation variables characterized by five equations:

$$\begin{cases} Wx= & (Tx_B + \Delta Tx_B) + (Tx_A + Px_0 + \Delta Fx_0)cosB \\ & -[(Tz_A + \Delta Tz_A) - (Py_0 + \Delta Fy_0)sinA \\ & +(Pz_0 + \Delta Fz_0)cosA]sinB \\ Wy= & (Ty_B + Ty_A + \Delta Ty_A) + (Py_0 + \Delta Fy_0)cosA \\ & +(Pz_0 + \Delta Fz_0)sinA \\ Wz= & (Tz_B + \Delta Tz_B) + (Tx_A + Px_0 + \Delta Fx_0)sinB \\ & +[(Tz_A + \Delta Tz_A) - (Py_0 + \Delta Fy_0)sinA \\ & +(Pz_0 + \Delta Fz_0)cosA]cosB \\ W_A= & A + \Delta A \\ W_B= & B + \Delta B \end{cases} \tag{1}$$

Where (Wx, Wy, Wz, W_A, W_B) is the coordinates of the part origin relative to machine zero. The part location P_0 (Px_o, Py_o, Pz_o) error (see Fig. 1) is incorporated within the fixture error. In Fig. 1, T is the table center coordinate system and F_0 is the fixture center coordinate system; the part is rigidly located and clamped down on the fixture. The origin of the Global offset system is on the part center P_s (Px_o, Py_o, Pz_o). The CMM system origin is also on the part center Ps. The orientation of the CMM system is determined by the print datum and CMM measurement convenience. The Global offset is made up by the following nine compensation variables:

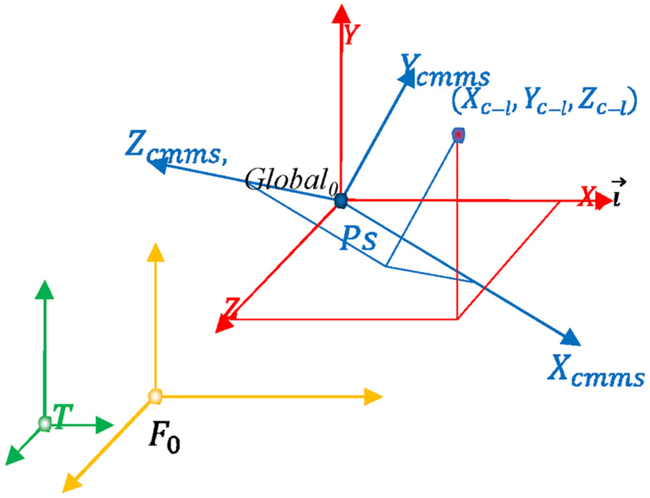

Fig. 1. Global machine and CMM coordinates of a feature.

- Two table offset variables (ΔTy_A, ΔTz_A) for offsetting the A-table in the Y and Z directions.
- Two table offset variables (ΔTx_B, ΔTz_B) for offsetting the B-table in the X and Z directions.
- Three fixture offset variables (ΔFx_O, ΔFy_O, ΔFz_O) for offsetting the fixture attached to the A-table in the X, Y, and Z directions.
- Two rotation offset variables (ΔA, ΔB) in the A and B table directions.

Regardless of the specific set-up of the 5-axis CNC machine, the nine global compensation variables will be combined to offset the location of the workpiece within the process program of the CNC machine to more-accurately produce workpieces matching the design of the part.

Considering the CMM system virtually sitting on the part origin Po that is called the part coordinate system (PCS) and it has the same orientation as the machine coordinate system (MCS), the compensation system of equations is:

$$\begin{gathered} cosB\Delta Tx_B + sinB\Delta Tz_B + \Delta Fx_0 \\ +[Tz_A - (Fy_0 + Py_0 + Y_{cmm})sinA \\ +(Fz_0 + Pz_0 + Z_{cmm})cosA]\Delta B = -\Delta X_{cmm} \\ cosA\Delta Ty_A - sinA\Delta Tz_A + sinAsinB\Delta Tx_B \\ -sinAcosB\Delta Tz_B + \Delta Fy_0 - (Fz_0 + Pz_0 + Z_{cmm})\Delta A \\ +(Tx_A + Fx_0 + Px_0 + X_{cmm})sinA\Delta B = -\Delta Y_{cmm} \\ sinA\Delta Ty_A + cosA\Delta Tz_A - cosAsinB\Delta Tx_B \\ +cosAcosB\Delta Tz_B + \Delta Fz_0 - (Fy_0 + Py_0 + Y_{cmm})\Delta A \\ -(Tx_A + Fx_0 + Px_0 + X_{cmm})cosA\Delta B = -\Delta Z_{cmm} \end{gathered} \tag{2}$$

In the above equation, it was assumed that the feature of interest is measured in the main CMM system, which is oriented in the same direction as the MCS when B = 0 and A = 0. However, a complex part (i.e. engine block, cylinder head, etc.) will have multiple machined features and they don't all have the same CMM system. Different part features are typically measured in different CMM systems due to the different datum reference frame used to control the features. When multiple features are using the same PCSm, they are grouped together under that PCSm system. Features measured in the PCSm and their nominals are transformed to the main CMM system to be incorporated in the Global offset estimation. This transformation is explained through an example in an earlier paper [2] and illustrated in Fig. 1 for a feature l Measured in PCSm.

After transforming the measurements of all features to the main CMM system, Eq. (2) can be written in matrix form for any feature location l:

$$\begin{bmatrix} c_{11l} & c_{12l} & c_{13l} & c_{14l} & c_{15l} & c_{16l} & c_{17l} & c_{18l} & c_{19l} \\ c_{21l} & c_{22l} & c_{23l} & c_{24l} & c_{25l} & c_{26l} & c_{27l} & c_{28l} & c_{29l} \\ c_{31l} & c_{32l} & c_{33l} & c_{34l} & c_{35l} & c_{36l} & c_{37l} & c_{38l} & c_{39l} \end{bmatrix}$$

$$\begin{bmatrix} \Delta Tx_A \\ \Delta Ty_A \\ \Delta Tx_B \\ \Delta Tz_B \\ \Delta Fx_0 \\ \Delta Fy_0 \\ \Delta Fz_0 \\ \Delta A \\ \Delta B \end{bmatrix} = \begin{bmatrix} \Delta X_l \\ \Delta Y_l \\ \Delta Z_l \end{bmatrix} \tag{3}$$

Eq. (3) describes the correction/offset for a single feature in global