Development of Computer Aided Calibration Module for CMMs and Machine Tools Using a Compensated Step Gauge

Heuijae Pahk* and Jonghoo Kim*

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This paper shows a micro computer aided error calibration system for CMMs and machine tools, which is a fast and efficient error calibration system : A micro computer stores the error calibration data of a step gauge which were precalibrated with more precise equipments such as laser interferometer, then the step gauge is probed with the specific CMMs or machine tools. The probing data are compared with the stored precalibration data, in order to give the linear displacement accuracy of the machines. High degree of computer integration has been performed in the measurement path planning, measurement operation, and error evaluation. Thus a rigorous computer aided error calibration system has been implemented with full potential of practical application to most of commercial CMMs and machine tools of CNC type.

Key Words: Error Calibration, Step Gauge, CMM, Machine Tool

1. Introduction

Error calibration and frequent reverfication of working accuracy of coordinate measuring machines and machine tools are currently acknowledged as essential processes in order to maintain high performance of the equipments and high quality of products. Expensive equipments such as laser interferometers and precision levels were conventionally used for the precise accuracy assessment, and the measurement tasks were very much time consuming and needed trained personnel for the operations.

On the other hand, mechanical artefacts such as step gauges were usually used for quick acceptance tests and error calibration in part, and their geometrical inaccuracy caused some limitations in practical error calibration.

For linear displacement accuracy of CMMs, many national standards such as ANSI/ASME B89, 1.12M•1985(1985), VDI/VDE-2617(1983, 1984), BS 6808(1987), and manufacturers association (CMMA) recommend laser interferometers, step gauges or block gauges. Laser interferometers were preferred for complete linear displacement error with high accuracy. However, a technical disadvantage of the laser interferometer is that the laser optics is inserted instead of measuring probe at the probe holder, the result is slightly different from the real measuring accuracy of the whole measuring system, and thus more prone to the practical machine performance. Thus a new measurement system is desirable for rapid, economic error assessment which also can achieve total measuring accuracy.

The development of micro computer and CNC controller technology enables a new error measurement/calibration system using calibrated mechanical artefacts where the data of the geometric inaccuracy (calibration data) are stored. And the measurement paths are generated for the probing of the mechanical artefacts, then error terms are evaluated from the comparison between the stored and measured data. Detail algorithms are implemented for the analysis.

The whole measurement/calibration procedures are computer controlled and driven by the

* Department of Industrial Engineering, POSTECH, Pohang, 790-784, Korea

developed user friendly software.

2. Step Gauge Calibration

Step gauge was partly used for acceptance tests or error calibration of CMMs and machine tools. In the developed system it is used in order to assess the geometrical errors and linear displacement accuracy. Prior to being used for the measurement tasks, thus they have been calibrated with respect to more precise equipments in a environment controlled room in cooperation with the KRISS(Korea Research Institute Standards and Science).

The step gauge is usually made of steel, and small blocks are positioned in nominally equal step, 10 mm block pitch in common, and both sides of the blocks are machined parallel. The real distance between the reference block and each blocks are of metrological importance, thus a specially designed length calibration systemwith laser interferometer is used to calibrate the block distances. Both sides of each block is calibrated and they are stored in a data file, Fig. 1 shows practical calibration data of a 600 mm step gauge.

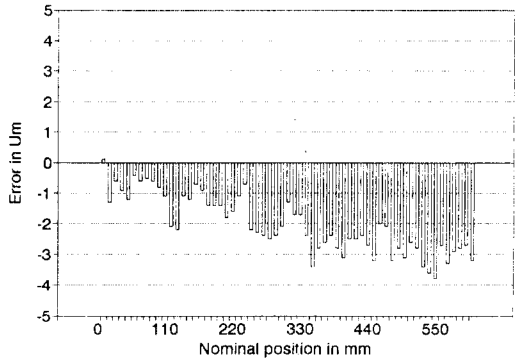

Fig. 1 Step gauge calibration

3. Path Plan Module for Gauge Measurement

Many modern CMMs of CNC type equip vector driving mechanism, with which target positions can be programmed in proper CNC command then machine moves to the target points, thus 3 dimensional motion can be planned.

Before planning the path, several intial points are probed in order to inform the CMM of location and position of the step gauge to be probed. As in Fig. 2, 16 points are initially probed, 8 points for the beginning block and the other 8 points for the end block. The cross product of vector P1P2, P1P3 determimes normal vector, N1, and the points P4, P5, P6, P7, P8 determines the width, height, and length of the beginning block. Centre point C1 of the block is obtained through some geometrical calculations with N1, P4, P5, P6, P7, and P8. The same operation is carried on to find the end block's centre point, C2. Vector

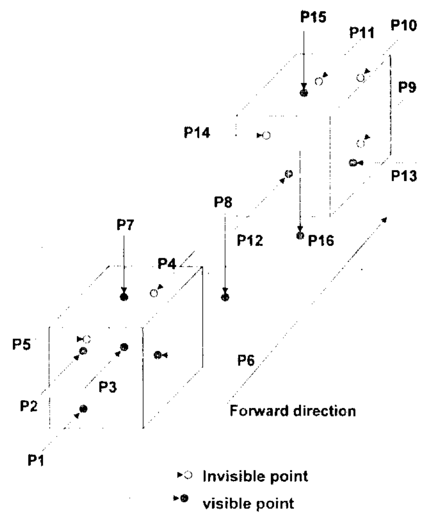

Fig. 2 Initial probing for location and position of the step gauge

C1C2 is used instead of N1 or N2 in planning the path to avoid possible misalignment of the normal vector N1 or N2, as they are evaluated from 3 points probing on small area surface of the blocks. The normal vector is to be calculated acurately in that it will be used for error evaluation in later stage.

The planned paths are generated in machine code for a specific CNC CMM. The idea of implementation of path planning for commercial CMMs are as follows.

Many modern CMMs have teaching mode in which specific measurement operation can be taught by operator, then the CNC system stores the input motions. In excution mode the stored informations (actually CNC machine codes for measurement operations) are retrieved and sent to the CNC controller, then executing the measurement operations. These facts show the possibility for intrusion of CNC codes from outside in the teaching mode. That is, if an algorithm can generate proper CNC codes for specific measurement operations, then the generated CNC codes can be passed to the execution mode as if they are from the teaching mode. Thus the path plan algorithm can now be implemented, which inputs initial probing points, then outputs corresponding CNC codes. The generated CNC codes are simulated in the computer screen which is provided by the CMM manufacturer. In case of step gauge measurement there are two possible ways of path plan, horizontal and vertical path. Figure 3 shows the two paths and operator is supposed to select the proper path in the system.

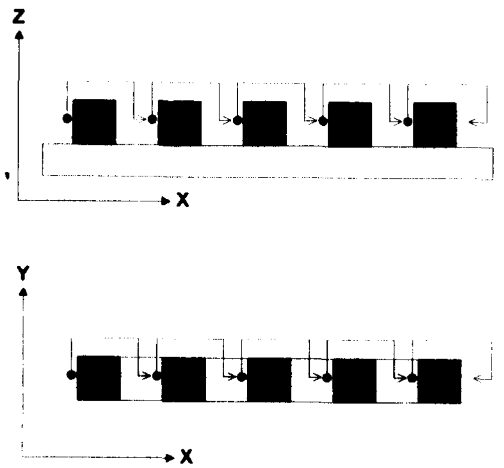

Fig. 3 Vertical and horizontal paths for step gauge

MV	0.000	0.000	400.000
PO 1			
MV	298.699	173.393	170.071
MV	298.699	173.393	150.071
MV	391.741	173.393	150.071
MS	397.741	173.393	150.071
PO 1			
MV	391.007	185.055	150.071
MS	396.960	185.807	150.071
PO 1			
MV	217.166	128.570	150.071
MS	211.908	125.680	150.071
PO 1			
MV	223.426	118.705	150.071
MS	218.572	115.178	150.071

Fig. 4 A typical CNC codes for step gauge measurement

After simulation on the computer screen, the CNC code is downloaded to the system in the execution mode, and the measurement operations are performed automatically. Figure 4 shows a typical example of the generated CNC codes for step gauge measurement.

4. Error Evaluation Module

The gauge probing data are saved into raw data files, and are ready for error evaluation. In this section, an error evaluation module is shown, where influence of machine errors can be calculated from linear diaplacement error from step gauge measurement.

4.1 Linear displacement from step gauge measurement

Similarly, the step gauge measurement results are processed to give linear displacement accuracy or length measurement error.

Calculation of effective radius of probe, R_{eff}

The CMM touch probe mainly consists of three parts : stylus tip, probe stylus, and probe body unit. Measuring force of touch probe, though it is supposed to be within few gram force, can cause elastic deformation of the probe stylus in combination with bending effects and springs of the probe body unit. Thus effective radius of the stylus tip is considered, and it is slightly smaller than the nominal radius of tip. In general, it is recommended that the effective radius, sometimes called pre-travel variation, is to be calculated in the same direction as measurements would take place.

The effective radius can be determined from measurement between neighboring blocks whose distance is known, where two close neighboring blocks are desirable in order to avoid possbible introduction of scale errors of the machine. The effective radius is

$$R_{eff} = \frac{(\text{measured block size} - \text{actual block size})}{2} \tag{1}$$

where actual block size is the calibrated block size from the calibration data file, and the effective radius calculation is automatically performed during the step gauge measurement.

The calculated effctive radius value is saved and then will be used for evaluating linear displacement accuracy from the step gauge measurement.

Evaluation of linear displacement accuracy

The linear displacement accuracy or length measurement error can now be calculated from the measurement data and the calibration data of the step gauge, because there would be no difference unless machine errors exist. As the blocks' sides are accessible from only one direction, say either forward or backward, shown in Fig. 5, error calculation is separately performed for front and back sides of the blocks.

As in Fig. 5 let $M_{2i-1,j}(X, Y, Z)$, $M_{2i,1}(X, Y, Z)$ be the jth measurement data at $(2i-1)$th location and $(2i)$th sides respectively, and S_{2i-1}, S_{2i} be the actual distance of $(2i-1)$th, $(2i)$th block sides from a reference point, respectively, which can be obtained from the calibration file of the step gauge. Then the errors at $(2i-1)$th, $(2i)$th sides can be evaluated as follows.

Let $XF_{2i-1,j}XB_{2i,j}$ be the jth forward backward measurement error at $(2i-1)$, $(2i)$th step, respectively.

$$XF_{2i-1,,j} = (M_{2i-1,j} - M_{ref}) - (S_{2i-1} - S_{ref}), \tag{2}$$

$$XB_{2i-,j} = (M_{2i,j} - M_{ref}) - (S_{2i} - S_{ref}), \tag{3}$$

where M_{ref} is the position of reference point, S_{ref} is actual distance of the reference point from the step gauge origin. It is noted that the measurement data are decomposed into the normal vector C1C2 direction in order to exclude any errors of the measuring probe on the block sides.

The forward positional error and two standard deviation can be evaluated from the repetitive forward measurement, and backward positional error and two standard deviation as well. Thus, forward and backward positional error XF_{2i-1}, $XB_{2i,j}$ and two standard deviation SF_{2i-1}, SB_{2i} are evaluated as follows.

$$XF_{2i-1} = \frac{1}{cycle}\sum_{j=1}^{cycle} XF_{2i-1,j}, \tag{4}$$

$$SF_{2i-1} = \sqrt{\frac{1}{(cycle-1)}\sum_{j=1}^{cycle}(XF_{2i-1} - XF_{2i-1,j})^2}, \tag{5}$$

$$XB_{2i} = \frac{1}{cycle}\sum_{j=1}^{cycle} XB_{2i,j}, \tag{6}$$

$$SB_{2i} = \sqrt{\frac{1}{(cycle-1)}\sum_{j=1}^{cycle}(XB_{2i} - XB_{2i,j})^2}, \tag{7}$$

where $cycle$ is the total number of repetitive measurement. In case of step gauge measurement, alternate step is either forward or backward direction, thus the intermediate step can be calculated from interpolation using neighbor blocks' measurement data. Therefore positional errors at the intermediate steps can be evaluated, that is,

$$XF_{2i} = \frac{(XF_{2i-1} + XF_{2i+1})}{2}, \tag{8}$$

$$XB_{2i-1} = \frac{(XF_{2i-2} + XB_{2i})}{2}, \tag{9}$$

and

$$SF_{2i} = \frac{(SF_{2i-1} + SF_{2i+1})}{2}, \tag{10}$$

$$SB_{2i-1} = \frac{(SB_{2i-2} + SB_{2i})}{2}, \tag{11}$$

thus XF_i, XB_i, SF_i, SB_i. $i = 1,2,3...$ are evaluated for at each blocks of the step gauge. The mean

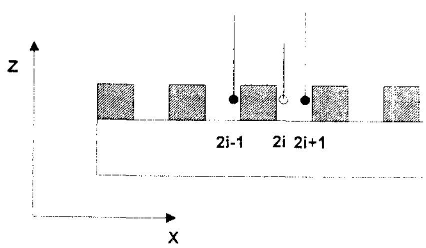

Fig. 5 Error evaluation for front and back sides in step gauge measurement

positional error, XM_i can now be calculated as the average of the forward and backward positional error.

$$XM_i = \frac{XF_i + XB_i}{2}, \tag{12}$$

and the reversal error, XR_i is the difference between the backward and forward measurement errors,

$$XR_i = XB_i - XF_i \tag{13}$$

4.2 Error presentation

Computer graghics environments are fully utilized that the evaluated errors are presented on computer screen, printer or plotter. In case of step gauge measurement, mean positional error, forward and backward positional errors are tabulated with corresponding nominal coordinates of CMM. Also, two standard deviation as well as the reversal error is tabulated at each nominal coordinates, thus complete linear displacement accuracy is performed. Practical examples for the step gauge measurement and the corresponding error evaluations are shown in section 5.

5. Practical Application of the Developed System and Discussions

A computer controlled commercial CMM of fixed bridge type was chosen for the practical measurement procedures which was installed in metrology lab in POSTECH, and it has to be mentioned that the machine was not in proper calibration state thus bears no relation to the real machine performance.

The gauge measurement system begins with locating the gauges in a working volume of the CMM, as the developed system allows all possible orientation and position for the gauges. Once located, the CMM probes the initial points on the gauges, 16 points for step gauge for proper path

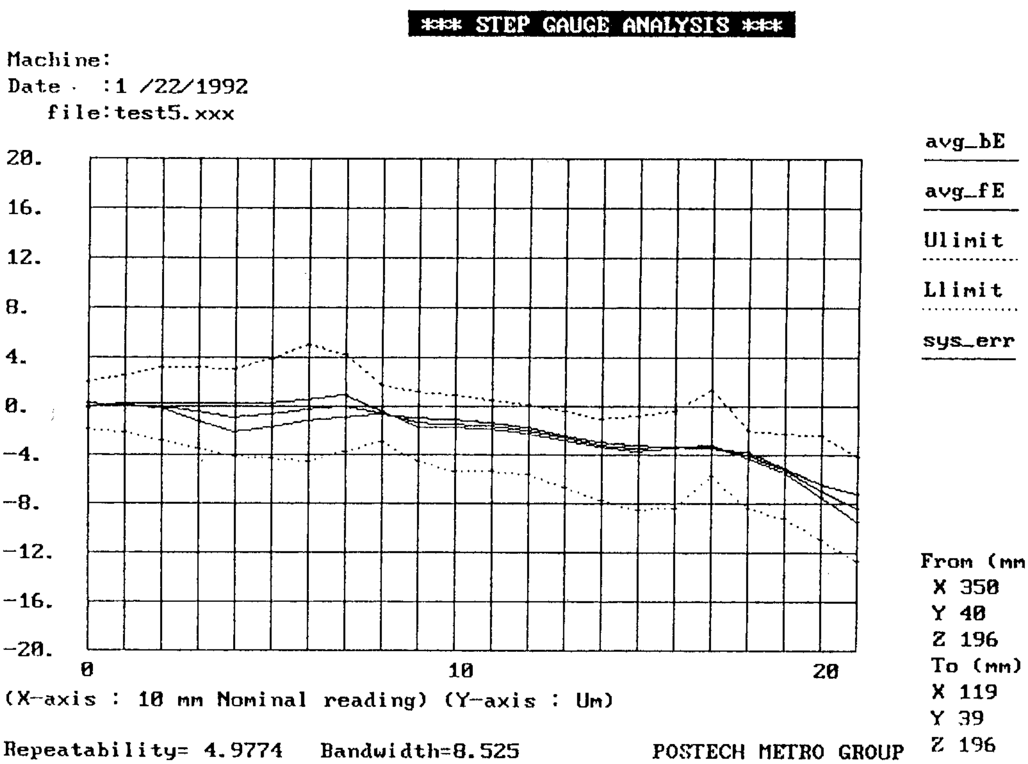

Fig. 6 X axis calibration

plan, and the probing data for initial probing are then saved in a temporary file. The developed path plan module is now loaded, and inputs the initial probing data, relevant data such as step size or number of division. Then the path plan is performed and the corresponding CNC code is generated for the CMM controller. The CNC code is saved in a data file, and is ready for graphical simulation or execution of the measurement operation. As the CMM performs measurement, the measured data are displayed on the computer screen and saved in a raw datafile. The error evaluation algorithm is now loaded, and the system asks operator to choose two file names : one is the file of gauge calibration and the other is the raw data file of gauge measurement for comparison. In case of step gauge, the position number (or indexing number) of beginning and end blocks of the step gauge has to input in the error evalution stage, as the measured section of the step gauge is to be informed for accurate calculation. Then the error evaluation module is loaded, and error calculations are performed, as explained in the previous section.

A step gauge is located and measured in a working volume of a CMM. The measurement and analysis procedures are followed as mentioned in the above. As results, the X positional error is shown in Fig. 6 giving 8.5 um bandwidth over 230 mm measurement span and 5.0 um repeatibility, which is two standard deviation of 5 repetitive measurements.

As mentioned above, the step gauge measurement can be performed for any orientation in the working volume, thus a diagonal direction is chosen for metrological interest in the working volume. Figure 7 shows the calibration result along the diagonal direction, (364, 297, 195) to (225, 64, 195) mm position in the machine, giving 20.5 um bandwidth over 270 mm measurement span.

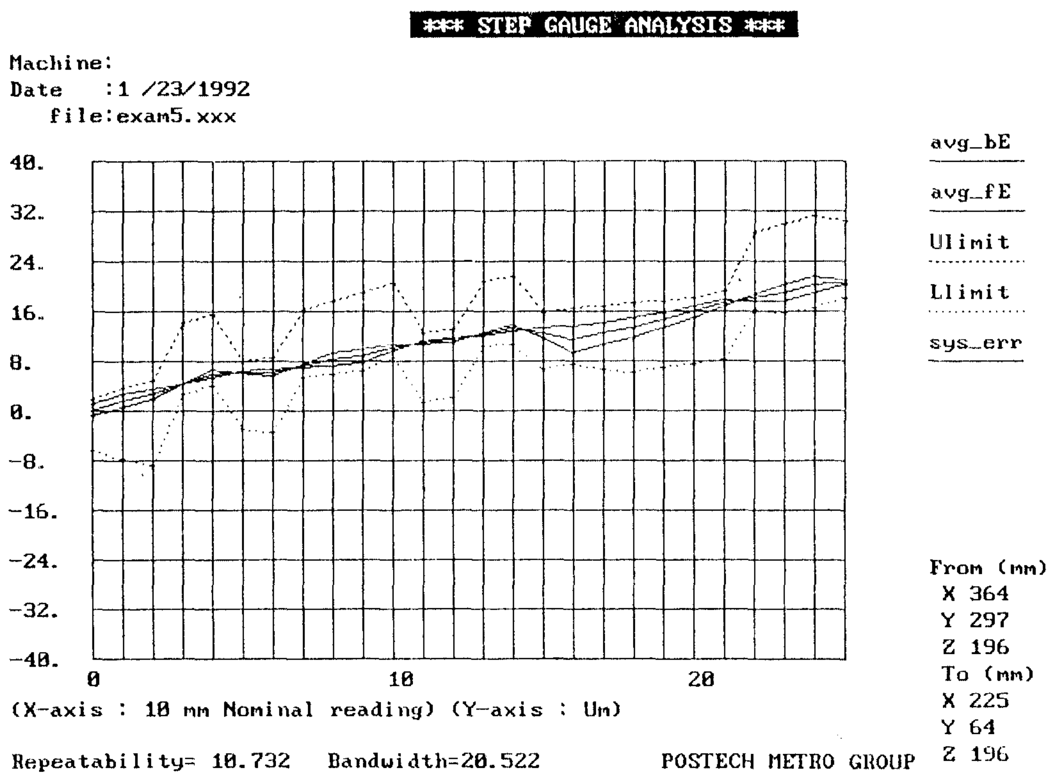

Fig. 7 Diagonal calibration

6. Conclusion and Suggestions for Further Works

Conclusion

(1) Computer integrated measurement/error calibration system is developed, where path planning, measurement operation, error calculation, and geometric error presentation are efficiently performed around a commercial CMM and micro computer.

(2) Calibrated mechanical artifacts are found to be useful for assessing machine errors in terms of total measuring accuracy, where their geometric inaccuracies are stored in a form of data file, and are used in error evaluation stage.

(4) For precise error analysis using touch probe, the effective radius evaluation algorithm is implemented, where the effective radius term is calculated automatically in step gauge measurement.

(5) A complete algorithm for linear displacement accuracy (length measurement) of a commercial CMM is implemented with touch probe and calibrated step gauges.

(6) Path plan module for gauge measurement is found to be efficient, where proper paths are planned, simulated, then executed for real measurement operation. Especially, because the path plan module invokes TEACH MODE of a commercial CMM, the developed system can be easily applied to other commercial CMMs.

(7) The developed system is found to be fast and efficient system, thus practical error measurement/calibration are performed in very short time, thus it is applicable to day-to-day calibration or frequent reverification of CMMs.

Suggestions for further research

The path plan module is desirable to generate path plans in universal CNC code such as DMIS, though a specific CNC code is adopted at the moment.

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