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RELIABILITY OF PARAMETRIC ERROR ON CALIBRATION OF CMM

M. Abbe [1], K. Takamasu [2] and S. Ozono [2]
[1] Mitutoyo Corporation, 1-20-1, Sakato, Takatsu, Kawasaki, 213-0012, Japan
[2] The University of Tokyo, 7-3-1, Hongo, Bunkyo, Tokyo, 113-8656, Japan

Abstract: This paper presents a method which is able to describe the reliability of the parametric error as the calibration result of a CMM. The reliability range may provide uncertainty indication of the calibration. Emphasis is placed on description of expansion of the propagation of error on the linear system expressing the parametric errors of a CMM, and confirmation of the method through the simulation on the calibration performed only by linear displacement measurements.
Keywords:CMM, Calibration, Parametric Error, Reliability

1 INTRODUCTION

Since numerical compensation technique was adopted on the coordinate measuring machine (CMM), ratio of cost and performance has been remarkably improved. It is now recognized as one of the key technology for commercially available CMMs [1,2]. With expansion of application field of CMMs, importance of the calibration of CMMs is increasing. However, a smart way to quantify reliability of calibration measurement itself seems not to be established. Typical calibration measurement requires following inspection measurement which partly verifies the validity of the calibration by adopting independent observation scheme. The verification measurement may normally reflect only a limited aspect of the CMM. Even if the complete verification measurement is so performed as to provide all 21 parametric errors, it requires effort in double.

Authors propose a new approach to investigate statistically predicted reliability of the calibration result [8,9,10]. The approach applies and expands the propagation of error on the linear system to the calibration of CMMs. Adopting the approach, reliability of the calibration activity in the respective parametric error or even in any combination of them can be statistically predicted.

First, the integrated model is introduced. The model has a particular characteristic that it provides not only the parametric errors of a CMM as the calibration result, but also the reliability range of the parametric error simultaneously. Basic concept of the model implementation is given. Next, a result from a simulation experiment is presented to confirm functionality of the model. The brute force method [3,4] with the laser interferometer is chosen as a simulation example. The method typically consists of a combination of simple linear displacement measurements which contribute toward corresponding parametric error in indirect manner. Though simple accumulation of variance contribution as former studies do hardly works in this case, it is shown that the proposed integrated model is able to predict reliability range of the estimated parametric error.

2 INTEGRATED MODEL

Importance of estimating uncertainty of geometric calibration activity is widely recognized. Considering state of calibration of CMMs, only limited possibilities has been realized. The fact can be due to the complex structure, too many contributions to be included, and so on. Furthermore, it should be noted that uncertainty of the calibration result is affected by variance in raw observation and also both the measurement and evaluation strategy actually adopted. The fact enlarges difficulty to analyze the uncertainty with in a complex measurement system, such as a CMM.

The integrated model is proposed in this report to overcome the difficulty. The schematic diagram is shown in Fig. 1. Functionality of the model partly resembles that described in former studies on the point of estimation of the parametric errors [e.g. 3,6]. The linear parameter model is built and is solved conventionally. A unique characteristic of the model is integration of the error propagation model which predicts the propagated reliability by being transferred the design matrix holding whole the attribute of the calibration measurement from the kinematic error model. Adding to variance with in the raw observation data, contribution made by the measurement strategy practically adopted can be statistically evaluated too.

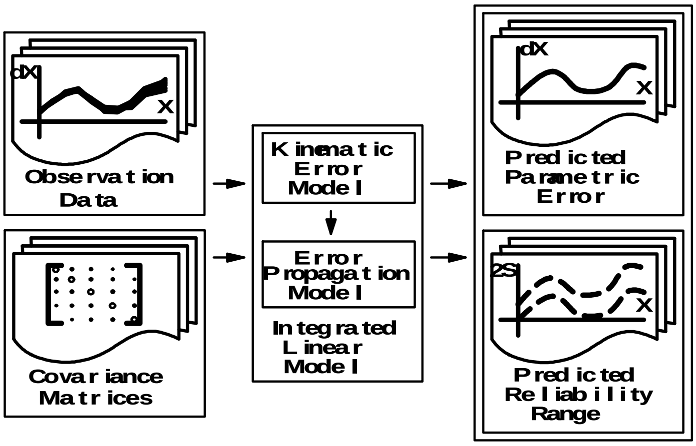


Figure 1. Schematic of integrated model

2.1 Propagation of Error

Geometric calibration of CMMs is typically performed in the sequential manner. Each of the components to be calibrated is assessed, more or less, independently and serially in sequence. Quality indication of the calibration measurement can be known in fragments as the estimation residual on each of the calculation step. However, overall indication is not.

Building a set of the linear equations the parametric errors can be estimated by one step calculation. Former studies adopting this approach focus on realization of the self-calibration method by the linear equations including unknown parameters for the standard to be referred to through the calibration [6,7].

With the characteristic explained as clear and evident process of the propagation of the error in the linear equations, the major benefit of the one step calculation is fully utilized.

2.2 Effect of Measurement Strategy

Various measurement techniques have been developed for CMM calibration [1]. One dimensional displacement measurement has been a typical one. Linear displacement measurement by the laser interferometer is one of the examples, and is widely adopted in spite of its tedious operation. Conventionally, measurement strategy by the laser interferometer was designed in the component by component manner. A performed measurement corresponds to respective parametric errors. Therefore, calculation of the parametric errors can be done by the component by component manner, which is rather simple to implement.

Indirect method was considered mainly for automation possibility. The method was often called as the brute force method [3]. Adopting it, measurement strategy applied does not have to correspond to the respective parametric error directly, but enough number of independent measurements are performed to keep full rank on the design matrix in case of the linear model solution. Since the measurement data are indirect to the parametric errors, adoption of the one step calculation is required. Reliability of the estimated parametric errors is not visible by conventional approach, since the estimation process is indirect. Simple accumulation of variance contributions seems hardly to work.

One step calculation method holds characteristic of the measurement strategy and contribution of the raw observation error in the design matrix in case of the linear solution, and transfers them to the calibration result. Extracting the design matrix from the kinematic error model and handing it to the error propagation model, Reliability of the calibration result can be statistically predicted by applying the propagation of error.

2.3 Statistical Information in Observation

The integrated model expects statistical information from the obserbation data in the form of a covariance matrix, which can be formulated by variance and correlation information. Uncertainty of a raw observation is quantified in the form of standard deviation. Sufficient statistical information for the integrated model is prepared, if correlation information is known.

It is not particular for calibration bodies nowadays to state raw uncertainty in calibration measurement under commercial situation. However, the uncertainty is normally concluded under assumption of the worst permissible environment condition. Actual uncertainty in the measurement can be better than that of clamed in the quality documents, and therefore it is unknown. Simply believing the claimed uncertainty the integrated model provides over estimated reliability on the parametric errors as the calibration result. Some over estimation through the practical calibration activity is in the safer side, and less problem causing. But the situation is not convenient one for the simulation experiment in this study.

Although dependence between respective observation points can not be bypassed, correlation information of observation data is hardly available in practice.

Numerical generation of simulated measurement data is executed to avoid these problems. The method consists of the eigenvalues decomposition and the following re-composition based on the linear combination of the independent vectors built by the corresponding eigenvectors and the eigenvalues. The schematic is shown in Fig. 2.

Extended uncertainty with 95% probability of an observation data by the laser interferometer is formulated by an expression shown in the equation (1).

$$S_{Meas} = a + b \times l_{Observ} \tag{1}$$

Where, a expresses the random term which is independent to the observation length l_{Observ} ,and b does the length dependant term. Probability distribution of the error function is assumed to show the normal distribution.

Variance information for the integrated model is easily calculated from the extended uncertainty. Since correlation information is not available, it is desirable to know reasonable values in respective situation. An assumed value is to be adopted in this report.

An observation data following assigned statistical process is numerically generated by algebraic operation in this study. Where, variance and correlation represents characteristic of the statistical process. Possibility to have simulation data with evident statistical process is realized.

3 SIMULATION

The indirect measurement method, often called as the brute force method, is adopted as a simulation example. Measurement strategy of the indirect method is so designed as it is able to derive all the parametric errors from a sufficient number of observation data. Major components are affected by a combination of the plural observation measurements. Direct relation between the observation and the calibration result is not visible. As far as authors survey, no former study was performed to predict the statistically propagated variance especially on the indirect method.

The integrated model has the characteristic that enables us to predict reliability of the parametric errors of a CMM, even if direct relation between the observation and the parametric errors does not exist.

3.1 Measurement Strategy

A measurement strategy for the indirect method is designed to perform the simulation. Typical one is composed by a set of the one dimensional length measurement performed by the laser interferometer. Adding to the longitudinal linear position error components along axes, straightness error and rotation error components are estimated algebraically. Since the error propagation process is indirect too, reliability of the calibration result obtained by this method is not apparent.

Xhang et al reported a possibility of the calibration of a CMM by combining 22 linear displacement measurement in the volume [4]. The calculation method was in component by component manner. Calibration result was verified by the independent inspection measurement. Soons et al performed similar calibration with combination of length measurement [3]. Estimation was done by the one step calculation method. The reliability of the result was again indicated by the independent inspection measurement. Assessment of the calibration itself seems not to be performed until now.

Though detail is not described here, a measurement strategy consisting of 21 linear displacement in the volume is designed empirically as shown in Fig. 3. The 21 lines are allocated in the volume as they are algebraically independent. Estimation of 21 parametric errors is possible by adopting the strategy instead of no extra redundancy.

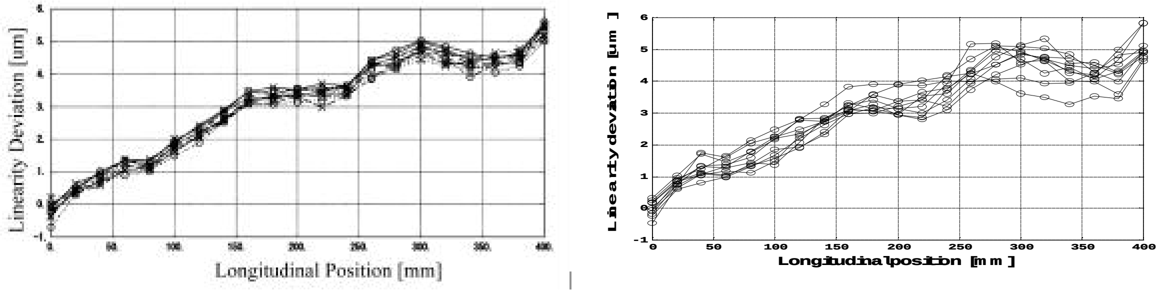
3.2 Numerically Generated Observation Data

The integrated model expects to know variance and correlation information of the observation measurement as mentioned. Introduced extended uncertainty for the simulation is as shown in the equation (2).

$$2S[mm] = 0.2 + 0.7 \times l[m] \tag{2}$$

This value is adopted as a typical one when the conventional laser interferometer system from Hewlett and Packard is applied for CMM calibration. There can be some variation under a practical situation depending on instrument type used and environmental condition assumed. The value in this paper can be an example. Although next concern is determination of correlation information for the observation measurement, it is not available under the practical situation. Equation (3) shows an assumed correlation. The value may need future verification on actual calibration site.

$$\begin{aligned} r &= 1 - 10 \times l[m] \qquad && if\ l \le 0.1[m] \\ r &= 0 && if\ l \ge 0.1[m] \end{aligned} \tag{3}$$



(a) Measured data on real CMM (b) Numerically generated data

Figure 4. Example of observation data, linear position error in *Y* axis.

The left plot in Fig. 4 shows an example of the observation measurement obtained by the laser interferometer experimentally according to the calibration procedure conforming to the equation (2). The right one does an example of the data numerically generated by following scheme in Fig. 2. Both plots show linear position error with 10 times repetitive go and back operation along *Y* axis. General trend conforms each other qualitatively. However clear comparison seems to be difficult. This fact is a major reason why the data for the simulation are generated by numerical operation.

Totally 21 set of linear displacement measurement which is just enough to perform estimation of the 21 set of the parametric errors of the CMM is generated numerically.

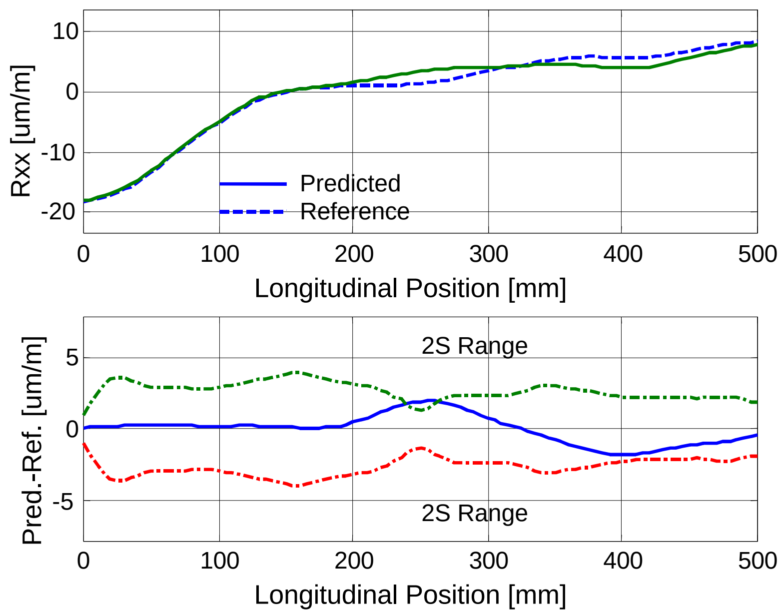


Figure 5 Example of result by integrated model

3.3 Estimated Result

The observation measurement is composed only by the linear displacement measurements. Reliability range of the estimated parametric errors is derived as to combine all the possible combination of the error contribution from the observation measurement and the measurement strategy.

Figure 5 shows a roll component of *X* axis as an example of the predicted reliability of the estimated parametric error by the integrated model. The top plot draws curves over the axis travel for the reference parametric error and the estimated one through the integrated model by a broken line and a solid one respectively. The bottom plot indicates conformity between these two curves. The integrated model provides predicted reliability of the parametric error by variance. Here twice of the predicted standard deviation is defined as 2S value and drawn on the bottom plot. Allowing 95% probability on the estimated parametric error curve it is expectable for the estimated parametric error curve to lay with in range made by 2S value. It is seen that the predicted reliability range seems to be able to express the practical reliability range of the calibration result. It is believed that this method may provide valuable information to establish the uncertainty indication on geometric calibration of CMMs.

4 CONCLUSION

A new approach, adoption of the integrated model, is proposed to predict statistically calculated reliability of the parametric error. The approach deals with all the possible statistical combination as far as the integrated model expresses. A simulation is performed to confirm the basic functionality of the integrated model. First, observation data for the measurement strategy composed only by 21 of linear displacement are generated by algebraic emulation. The emulated data are prepared for the simulation as to follow the assumed statistical process expressing uncertainty in the calibration measurement under the practical situation.

Estimation of the parametric errors of a CMM is executed by applying the emulated data on the integrated model. The estimated parametric error shows deviation from the ideal one due to variance in the observation data and is affected by the adopted measurement strategy too. It is shown that the deviation within the predicted parametric error lays with in the reliability range predicted by the integrated model, even if the measurement is performed only by 21 linear displacement measurements.

It is concluded that the proposed integrated model can be effective to establish reliability indication on the geometric calibration of CMMs in the practical situation. Since the prediction process is considered algebraically strict as far as the integrated model handles, prediction ability is not limited by the measurement strategy and instruments adopted.

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AUTHORS: Makoto ABBE, Ass. Prof. Dr. Kiyoshi TAKAMASU, Prof. Dr. Shigeo OZONO, Department of Precision Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo, Tokyo, 113-8656, Japan, Phone Int. +81-3-5841-6472, Fax Int. +81-3-5841-8556, E-mail: makoto@nano.pe.u-tokyo.ac.jp