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Basic concept of feature-based metrology

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Abstract

In coordinate metrology, an associated feature (or the Gaussian associated feature) is calculated from an extracted feature that is determined by a measured data set of a CMM (coordinate measuring machine) on a real feature using the least squares method. This data processing flow, which is called 'feature-based metrology' disagrees with the data processing methods in profile metrology and length measurement. In this report, the basic concepts of feature-based metrology are discussed, such as feature modeling, the least squares method and the statistical estimation of the uncertainty of measurement. Theoretical analysis and simulations for feature-based metrology in statistical ways directly imply that the basic concepts and data processing methods in this report are useful in estimating the uncertainty of measurement in coordinate metrology.

Keywords: Feature-based metrology; Coordinate measuring machine; Coordinate metrology

1. Introduction

In coordinate metrology, an associated feature is calculated from a measured data set on a real feature by a CMM (coordinate measuring machine). Then, the associated features are compared with the nominal features that are indicated on a drawing (Fig. 1). In this data processing method, the features are prime targets in calculating, evaluating and processing [1,2]. Consequently, this process is called 'feature-based metrology'. In this report, we discuss the following items to construct the basic concepts of feature-based metrology:

(i) the methods used to calculate geometrical parameters of features,
(ii) the selection of feature models,
(iii) the statistical estimation of the uncertainty of measurement of features and
(iv) the calculation method by which the uncertainty of related features is determined.

From theoretical analysis, simulations and these concepts, we have constructed data processing methods for feature-based metrology. It is implied that these methods and concepts in this report are useful in the estimation of the uncertainty of measurement in coordinate metrology.

2. Comparison of feature-based metrology and profile metrology

Table 1 shows the comparison of feature-based

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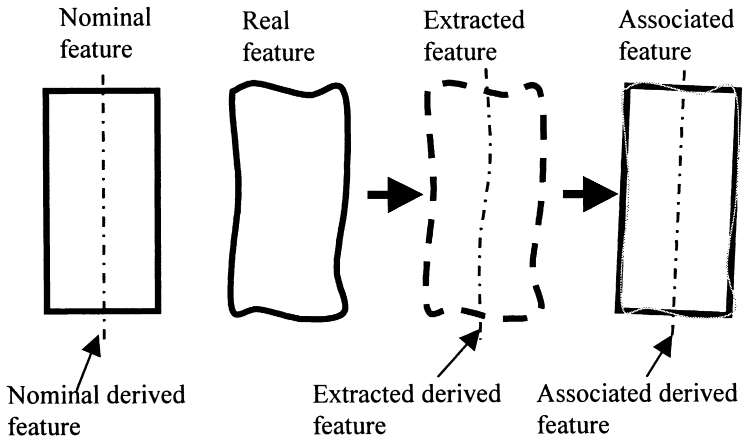

Fig. 1. Data processing flow in feature based metrology [1,2].

Table 1
Comparison of the feature-based metrology and the profile metrology

	Feature-based metrology	Profile metrology
Number of measured points	Small (10–20 in 3D)	Many (1000–10 000 in 3D)
Uncertainty of measured points	Large	Small
Density of measured points	Low (discrete sampling)	High (continuous sampling)
Data processing	Extrapolate, least squares method	Filtering
Objects of measurement	Parameters of feature	Profile
Model of feature	Yes	No

metrology and profile metrology. This comparison shows that the major differences are the number of measured points and the density of measured points. We should note that the number of measured points is small (only 10–20 points) on each feature in feature-based metrology. Therefore, we cannot calculate the geometrical parameters of the feature without the model of the feature. Furthermore, it is emphasized that extrapolation is used to define a related feature, such as the intersection line of two planes that is not measured directly by the CMM. From this, we conclude that the model of the features and the evaluation method of the uncertainty of measurement are key technical items in feature-based metrology [3].

3. Methods in feature-based metrology

3.1. Calculation of feature model

The least squares method is normally used for calculating the geometrical parameters of features from the measured data set [4,5]. This is because the least squares method is more accurate under the conditions in Table 1 than the minimum zone method for the following reasons:

(i) the uncertainty of calculation by the least squares method is estimated statistically and
(ii) the least squares method is more accurate when using a small number of measured points.

When the number of measured points is small, the deviation and the size of the confidence interval of the calculated features by the minimum zone method are larger than that by the least squares method. Because of this, we consider that the least squares method is better suited to feature-based metrology.

3.2. Selection of model

A key issue in using the least squares method is the selection of the model of the feature. Fig. 2 indicates the selection of the model for a data set of cubic equation with random errors. When the number of data is large and the error is small, the selection of the model is easy to determine if the curve is quadratic or cubic, using χ^2 testing (Fig. 2a). However, when the number of data is small and the error is large, it is difficult to determine an appropriate model of the curve (Fig. 2b). The selection of the model from a measured data set is difficult in feature-based metrology. This is because the condition of measurements in feature-based metrology (see Table 1) is similar to that in Fig. 2b. Because of this, we have to select the model of the feature from the nominal feature or using other information from designing and machining in the machine shop, as follows:

(i) use the same model of the nominal feature, when no other information of the measured feature is available,
(ii) use the lower degree model, when no information about the frequencies of form deviation of the measured feature is available (see Section 3.3), and
(iii) use the model of nominal feature with form deviation, when the frequency characteristic of the form deviation of the measured feature is known from information obtained by profile measurements or from information from the machine shop.

3.3. Uncertainty of feature

The uncertainty of each measured point is defined by an error analysis of the CMM and the probing system, and the results of profile measurement on each feature. From the uncertainty of the measured point, the uncertainty of the measured feature can be calculated statistically, using the following equations.

Eq. (1) shows an observation equation, a regular

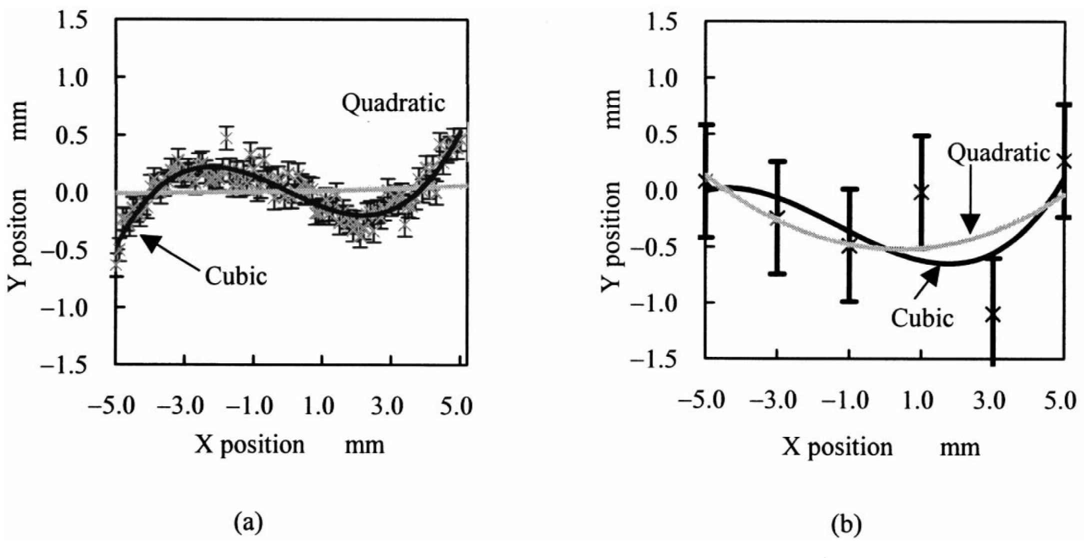

Fig. 2. Approximate curves of the measured profile which is generated by cubic equation ($y = 0.01x^3 - 0.15$) with random errors. (a) The number of data is 101 and the standard deviation is 0.1. (b) The number of data is 6 and the standard deviation is 0.5.

equation and a least squares solution, where **A** is a Jacobian matrix, **p** is a parameter vector, **S** is a matrix of the uncertainty of each measured point and **d** is the measured results [5]

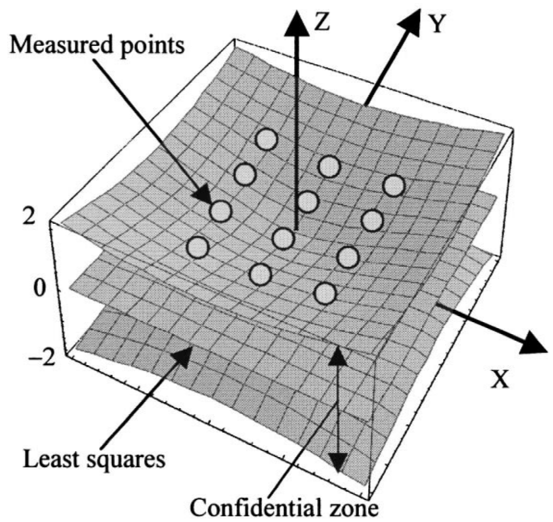

Fig. 3. Confidence interval of the measure plane, the number of the measured points is 12 and the standard deviation of each measured point is 1.0.

$$\begin{aligned}&\text{observation equation:} && \mathbf{d} = \mathbf{A}\mathbf{p}\\ &\text{regular equation:} && \tilde{\mathbf{A}}\mathbf{S}^{-1}\mathbf{A}\mathbf{p} = \tilde{\mathbf{A}}\mathbf{S}^{-1}\mathbf{d}\\ &\text{least squares solution:} && \mathbf{p} = (\tilde{\mathbf{A}}\mathbf{S}^{-1}\mathbf{A})\tilde{\mathbf{A}}\mathbf{S}^{-1}\mathbf{d}\end{aligned} \quad (1)$$

Using the propagation law of error of the least squares method, the error matrix of parameter $\mathbf{S}_p$, and the error matrix of observation $\mathbf{S}_m$ are calculated as Eq. (2) and Eq. (3), respectively. The matrix $\mathbf{S}_p$ indicates the uncertainty of each parameter and the matrix $\mathbf{S}_m$ indicates the uncertainty of measurement at each measured point [6]

$$\mathbf{S}_p = (\tilde{\mathbf{A}}\mathbf{S}^{-1}\mathbf{A})^{-1} \quad (2)$$

$$\mathbf{S}_m = \mathbf{A}\mathbf{S}_p\tilde{\mathbf{A}}. \quad (3)$$

Fig. 3 shows an example of an error analysis from 12 measured points on a flat plane. The middle plane is the least squares plane, the upper and lower planes indicate the upper and lower limits of the confidence interval of the feature, respectively. We note that the upper and lower limits of the confidence interval are equal to the range of the uncertainty of the measured feature. Using Eq. (3), the uncertainty at the position out of the measuring range also can be calculated.

Fig. 4 displays the confidence interval for extrapo-

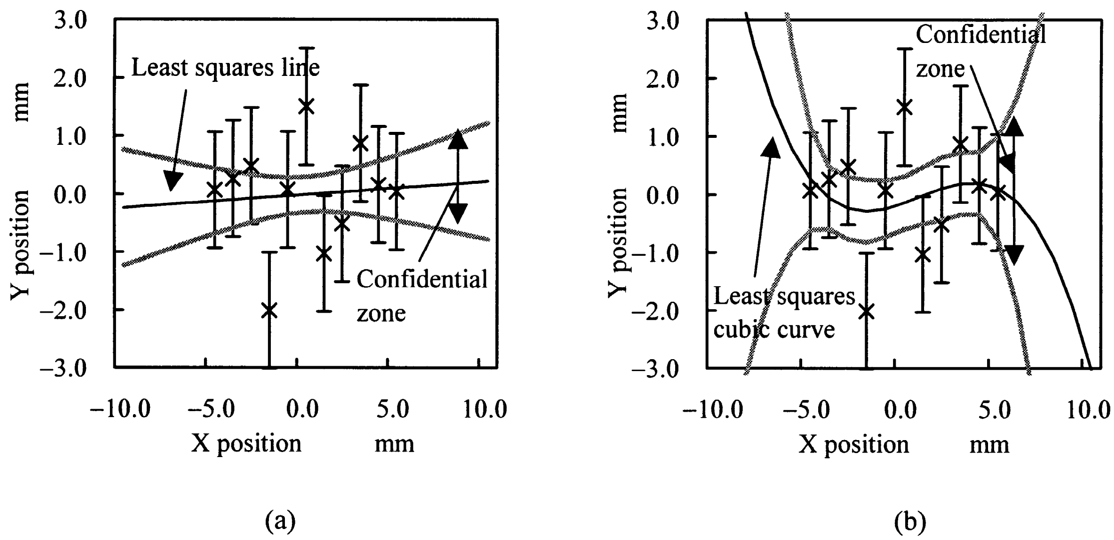

Fig. 4. Extrapolation of the feature by approximate of (a) linear equation and (b) cubic equation; the number of measured points is 11 and the standard deviation is 1.0.

lation of a least squares line and a least squares cubic curve for the same data set, which is generated from the cubic curve with large random errors. In the case of large random errors, the range of the confidence interval of the simple model (or the least squares line) is smaller than that of the complex model (or the least squares cubic curve) at the position out of the measuring range. This directly illustrates that the simple model is better suited to feature-based metrology with extrapolation.

3.4. Calculation of related feature

Fig. 5 displays the calculation concept of the relationship between an intersection line and two planes that cross at angle α. The confidence interval of the intersection line is calculated from the confidence intervals of two planes and angle α as Eq. (4). Where s_1 and s_2 are the uncertainty of two planes, s_s is the uncertainty of the intersection line

$$s_s = \frac{\sqrt{s_1^2 + s_2^2}}{\sin \alpha} \quad (4)$$

Thus, the uncertainty of the related features, such as intersection lines, intersection points and intersection circles, can be estimated using this method of calculation and these concepts [7].

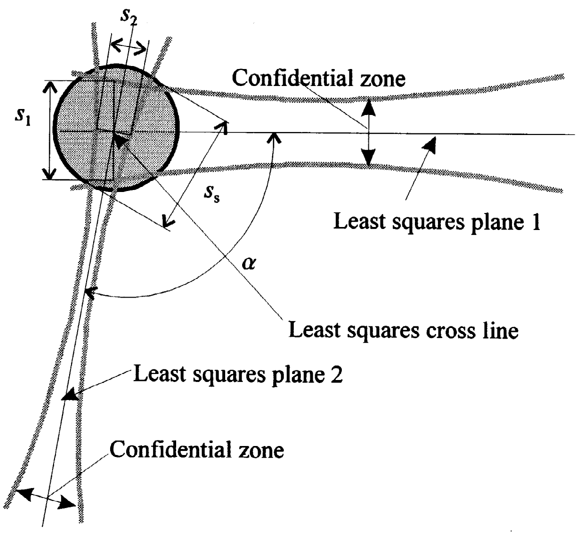

Fig. 5. Confidential zone of the cross line by two plane features with the confidential zones.

4. Processing flow in feature-based metrology

From the methods of feature-based metrology discussed in Section 3, the uncertainty of measurement in feature-based metrology is calculated using the following five steps:

(i) measuring several points on each feature by the CMM,
(ii) selecting the model of each feature by information obtained from drawings, design or machining,
(iii) calculating the geometric parameters and size of the confidence interval (uncertainty) of each feature,
(iv) calculating the geometric parameters and size of the confidence interval (uncertainty) of related features,
(v) comparing and evaluating the geometric parameters and the uncertainty of measurement of each feature with dimensions and tolerance zones indicated in drawings.

5. Conclusion and future works

In this report, we have evaluated the basic concepts of feature-based metrology, which are used in coordinate metrology, and we have constructed its data processing flow using a CMM. Our theoretical analysis has caused us to reach the following conclusions:

(i) the least squares method is better suited to calculate the geometric parameters and the uncertainty of features,
(ii) the simple (or low degree) model is better fitted to the model of the feature in the condition of feature-based metrology,
(iii) the calculation method of the uncertainty of feature is presented using the least squares method and statistical evaluation,
(iv) the calculation method of the uncertainty of related feature is also presented.

Further works in feature-based metrology are suggested as follows:

(i) how to define the uncertainty of each measured point in a CMM,
(ii) how to select the model of each feature and how to evaluate the function of the selection,
(iii) how to evaluate the results of measurement and how to compare geometric parameters and tolerancing, and
(iv) how to decide the strategy of measurement using feature-based metrology.

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