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Analysis and Control of Dimensioning and Geometric Tolerancing through Surface Topography Generation

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Abstract

A general quality assurance system to perform in-process inspection through on-line monitoring is proposed in this paper. Technical issues related to the model-based indirect measuring approach to retrace the quality control target are discussed. This research analyzes the dynamic characteristics of dimensioning and geometirc toleracing through surface topography generation through incorporation of random tool motion analysis in the evaluation of machining accuracy. Statistical methods for estimating metrological indices, such as roundness and straightness, have been developed to assist in the determination of control limits designed for on-line detection of disturbances external to the normal machining process.

1. Introduction

Ever increasing competition and higher production costs are forcing the manufacturing industry to seek technological innovations. One of the important goals in this endeavor is to maintain a consistently high level of product quality. This quality requirement has become more evident with the introduction of untended machining processes to the manufacturing industry. In such a computer-based automation environment, a reliable and advanced quality control program is desperately needed.

Traditional techniques of quality control such as control charts and reliability analysis are still widely used in practice (Grant, 1964 and Fiegenbaum, 1965). The scientific basis of these techniques is to identify the part of process variation which is inherently associated with the manufacturing process so that it may be separated from those parts of process variation which are caused by external disturbances. Thus, the external factors which are responsible for deteriation of product quality may be eliminated or corrected and a normal manufacturing process level of quality may be maintained. The longstanding efforts of Taguchi have also made considerable contributions toward the improvement of product quality and productivity (Taguchi and Wu, 1980). Taguchi has placed emphasis on pushing quality control farther upstream into engineering design, well ahead of manufacturing. The Taguchi method of parameter design focuses on finding the design parameter values which maximize manufacturing process robustness - having the variation of the product performance least sensitive to the factors which are most difficult to control during manufacturing. However, the effectiveness of all these approaches depends totally upon the product inspection process which provides quality assurance. The post-process inspection is passive because the defect products have already been made when the inspection process starts.

It is evident that avoiding the production of bad products during the manufacturing process should be the focus of any advanced quality assurance system. Recently, a quality in automation concept has been proposed for the control of machining processes (Lovett, 1989). This concept advocates a quality assurance system that integrates sensor technology and metrology methods to perform on-line quality inspection. During the machining process, this system monitors, measures, and controls significant parameters of the manufacturing process and the machine tool. These functions are performed for the purpose of on-line detection of possible interferences with the normal machining process, which is caused by external deterioration factors, such as tool wear and temperature variation of the machine tool. This new concept represents a significant step forward in the efforts to improve productivity and quality in computer-based production automation environments. However, much work has to be done before the concept of quality in automation can be well defined and, thereafter, accepted by the manufacturing industry.

This paper presents a study aimed at reducing the reliance of quality control on traditional post-process inspection and providing a reliable model, which relates the sensing signal(s) to the required machining quality specifications for in-process verification. To narrow the presentation scope, this paper focuses specifically on the analysis and control of dimensioning and geometric tolerancing through surface topography generation. By tracing the tool vibratory motion with on-line signal detection and processing, this study carries out identification of dimensional variation and variation of geometrical features, such as the roundness of a surface of revolution and the straightness of a cylinder during machining. In addition, effects of basic material properties, such as hardness and ductility on machining accuracy are quantitatively evaluated. This evaluation forms a basis not only for the establishment of on-line control limits which reduces the possibility of false alarming, but also for the formulation an off-line strategy to control machining accuracy through material property characterization.

2. On-Line Evaluation of Dimensioning and Geometric Tolerancing

The main technical issues involved in the development of an on-line quality inspection system are real-time sensing, signal processing, and decision making based on the in-process verification of dimensioning and geometric tolerancing (Danai and Ulsoy, 1987 and Lovett, 1989). There are two basic approaches to implement these technical concerns. The first approach is called in-process verification through direct measurement. An illustrative example of this approach is the direct measurement of the workpiece diameter while it is being machined. The direct measurement approach is extremely desirable because the measured information can be utilized by the decision maker without interpretation (Weck and Schmit, 1986 and Kohno, etc., 1989). However, this approach requires special preparation of the measuring device which is usually costly. Another possible drawback associated with the direct measurement approach is its incapability of identifying the factor(s) causing the quality deterioration. For example, consider a measured diameter dimension which is found to be above the upper tolerance limit. This situation could be due to either a misplacement of the cutting tool, or to tool wear during machining. Such information is required by the decision maker to take action toward elimination of external disturbance(s) to maintain the normal machining process. For example, the former cause requires only correction of the cutting tool position while the latter requires tool replacement.

The second approach is called in-process verification through indirect measurement (Pandit and Kashou, 1982 and Koren, et al., 1987). The basic methodology of the indirect measurement approach is that the on-line detected signal(s), such as the cutting force signal, and/or tool vibratory signal, does not directly reflect the quality control target, such as dimensional variation and variation of geometric tolerancing. However, a system model built on the inherent relationships between the detected signal(s) and the quality control target, may be used to retrace the dynamic variation of the quality control target based on the information extracted from the on-line detected signal(s). It is certain that the signal(s) chosen to be on-line detected should be sensitive to certain parameters, for example, the dynamic variation of dimensioning and geometric tolerancing during machining. In addition, by choosing the detected signal(s) which has its root on the physical mechanism(s) which causes the quality deterioration, the indirect measurement approach may offer valuable information for the purpose of control of machining accuracy.

2.1 Description of a General Quality Assurance System

The research work presented in this paper is based on the indirect measurement approach to address an on-line evaluation of dimensioning and geometric tolerancing.

Figure 1 outlines the general quality assurance system used in this research. This quality assurance system consists of six components. These six components represent: real-time sensing, signal processing, on-line retracing of tool motion, simulation of surface topography, evaluation of metrological indices, and inference mechanism for decision making. During machining, the cutting force and tool vibration are sensed by a designed transducer (Zhang, etc., 1986). The two detected signals are digitized, filtered, and analyzed to obtain synthesized information of cutting force and tool vibration. The synthesized information is fed to the indirect measurement model to retrace the instantaneous motion of the tool during machining. The retraced tool motion is used to simulate the surface topography formed during machining through integration of the tool geometric motion, such as the tool spiral motion during a single-point turning. The simulated surface topography forms a basis for the evaluation of metrological indices. The evaluated values of metrological indices are compared with the corresponding control limits predetermined by the quality assurance system. The inference mechanism, acting as a decision maker, controls the machining process through this on-line monitoring cycle.

Common sense dictates that the success of such a quality assurance system depends on the accuracy and effectiveness of the employed hardware and software. There is, however, another key factor, which cannot be overlooked upon. This factor is the reference data base (the shaded area shown in Fig. 1). This reference data base is used to establish the control limits for the inference mechanism to make decisions. A physical implication of setting the control limits for on-line monitoring is the detection of excessive variation of dimensioning and geometric tolerancing due to external disturbances, such as tool wear and heat deformation of the machine tool. Consequently, the monitoring sensitivity is linked to the positioning of control limits. Innovative methods to scientifically determine the inherent variation associated with an on-line monitoring process are needed.

2.2 Analysis of Dimensioning and Geometric Tolerancing

It has been known that the inherent variation of dimensioning and geometric tolerancing is as a result of tool vibratory motion. When the machining process reaches steady state, the random tool motion is the main cause of machining errors. Hence, an accurate prediction of the random tool motion is necessary for the identification of the inherent variation. A recent study has shown that the random excitation observed in practice is due mainly to the presence of nonhomogeneous distribution of hardness in the material being machined (Zhang, 1986). A statistical method was developed to quantitatively evaluate the random tool motion during the machining of workpiece materials having nonhomogeneous hardness distributions. In addition, the surface topography generated during machining was constructed through computer simulation to visualize the finish characteristics of a machined surface. The associated numerical database offers opportunities to quantify metrological characterization indices.

2.2.1 Basic Assumptions

The research work presented in this paper utilizes this statistical method to quantify the inherent variation during the on-line assessment of metrological indices, such as dimensioning and geometric tolerancing. In this research, the following assumptions are made.

1. Hardness variability in the material being machined is taken as a representative random excitation source during machining.
2. A mathematical model describing the single-point cutting operation, such as turning or boring, is used as a simulator to manipulate the random tool motion where the random excitation acts as an input to the simulator.

Based on these two assumptions, the surface texture formed during machining can be quantitatively visualized from the simulated tool path during machining. Surface topographies formed during machining, such as the one shown in Fig. 1, can be constructed through the integration of machine tool kinematics (for example, tool spiral trajectory due to feed and spindle rotatory motions during turning). As a result of the availability of a numerical data base of topography information, metrological characterization indices can be evaluated. Methods to evaluate the roundness on a surface of revolution, straightness of a cylindrical surface and their inherent variation under a given machining condition are presented below.

2.2.2 Estimation of Obtainable Accuracy of Dimensions

Figure 2a is a polar plot of the instantaneous tool positions during one revolution of the workpiece where a total $2n$ tool positions are assumed. This polar plot corresponds to a section view, in the direction normal to the feed motion, taken from the surface topography shown in Fig. 2b. Given this polar plot, we can have the following information related to the diameter dimensioning.

1. Maximum diameter, D_{max}, as illustrated in Fig. 2a.
2. Minimum diameter, D_{min}, as illustrated in Fig. 2a.
3. Mean value of the diameter dimensioning, $\overline{D}$, which is given by

$$\overline{D} = \frac{1}{n}\sum_{i=1}^{n} D_i \qquad (1)$$

where $D_i = \sqrt{(x_i - x_{n+i})^2 + (y_i - y_{n+i})^2}$

(x_i,y_i) and (x_{n+i},y_{n+i}) = coordinates of the two tool positions symmetric about the center.

4. Standard deviation of the diameter dimensioning, σ_D, is given by

$$\sigma_D = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(D_i - \overline{D})^2} \qquad (2)$$

If the numerical value of $\overline{D}$ represents the tool setting position under monitoring, the control limits should be placed at $\overline{D} \pm 3\,\sigma_D$ for the on-line monitoring. This implies that the variation of tool position within these upper and lower limits is interpreted as an inherent nature of the normal machining process.

2.2.3 Estimation of Roundness

The roundness on a surface of revolution, based on ANSI (ANSI Y14.5, 1985) and Foster (1986), is defined as the minimum separation of two bounding concentric circles. For a given polar plot of instantaneous tool positions during one revolution of the workpiece (as shown in Fig. 2a) three quantities are needed for the evaluation of roundness, i.e., the center of two bounding concentric circles, the inner bounding circle, and the outer bounding circle. A procedure, which consists of three steps, has been developed for the evaluation of roundness.

1. Determination of the center coordinates, (C_x,C_y). As shown in Fig. 3, a radial vector is assigned to the midpoint of each pair of (x_i,y_i) and (x_{n+i},y_{n+i}). This vector is characterized by its length, ρ_i, and directional angle, θ_i. Their numerical values are given by

$$\rho_i = \sqrt{\left[\frac{x_i + x_{n+i}}{2}\right]^2 + \left[\frac{y_i + y_{n+i}}{2}\right]^2} \qquad (3)$$

$$\theta_i = \tan^{-1}\frac{y_i + y_{n+i}}{x_i + x_{n+i}} \qquad (4)$$

A method to calculate the centroid of a discrete lumped mass distribution for the determination of the center coordinates has been adopted as given below

$$C_x = \frac{1}{n}\sum_{i=1}^{n}\rho_i \cos\theta_i$$

(5)

$$C_y = \frac{1}{n}\sum_{i=1}^{n}\rho_i \sin\theta_i$$

2. Determination of the inner and outer bounding circles, D_{inner} and D_{outer}, which are given by

$$\frac{D_{inner}}{2} = \mathrm{Min}\left\{\sqrt{(x_i - C_x)^2 + (y_i - C_y{}^2)}\right\} \tag{6}$$

$$\frac{D_{outer}}{2} = \mathrm{Max}\left\{\sqrt{(x_i - C_x)^2 + (y_i - C_y{}^2)}\right\} \tag{7}$$

3. Determination of the roundness, which is given by

$$\mathrm{Roundness} = RN = \frac{D_{outer}}{2} - \frac{D_{inner}}{2} \tag{8}$$

In Fig. 2a, the roundness value as well as the inner and outer bounding circles are illustrated. Note that the manipulated roundness value varies from section to section, and should be dealt with statistically. For the purpose of on-line monitoring, a similar procedure should be followed to establish the control limits, such as $\overline{RN} \pm 3\,\sigma_{rn}$ where

$$\overline{RN} = \frac{1}{m}\sum_{j=1}^{m} RN_j \tag{9}$$

$$\sigma_{rn} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(RN_j - \overline{RN})^2} \tag{10}$$

Note that the index *m* stands for the number of sections needed to establish the control limits at the initial stage of the on-line monitoring process.

2.2.4 Estimation of Straightness

Straightness is a condition where an element of a surface or an axis is a straight line. Straightness tolerance is the deviation from linearity of the trace of a line element on a feature, such as a cylindrical surface. The tolerance zone of the straightness of a line is bounded by the two closest parallel lines which enclose all inspection points between them. Developing methods or algorithms to efficiently locate the two parallel lines has been a task in the metrological research (Lai and Wang, 1988).

A new method, which applies a linear regression theorem for identification of the tolerance zone, has been developed in this research. This new method requires three steps.

1. Determination of the coordinates of the inspection points on a generating line. This requirement can be met if we take a cross section normal to the feed motion from the surface topography shown in Fig. 2b. The obtained surface roughness profile offers the coordinates of the inspection points. However, the surface roughness profiles differ from cross section to cross section, posing difficulty in selecting proper cross-section locations for the evaluation of straightness. An alternative way to determine the coordinates is to utilize parameters C_x, C_y, D_i, and θ_i, which are defined in the evaluation of dimensioning and roundness. Under the assumption that the cylindrical surface is made up of a series of ideal circles at individual cross sections, the coordinates of the inspection points on two generating lines are given by:

   On the horizontal orientation:

   $$X_j = C_{xj} + \sqrt{\left[\frac{\overline{D_j}}{2}\right]^2 - C_{yj}^2}, \quad \text{for } j = 1,2, ..., m \qquad (11)$$

   On the vertical orientation:

   $$Y_j = C_{yj} + \sqrt{\left[\frac{\overline{D_j}}{2}\right]^2 - C_{xj}^2}, \quad \text{for } j = 1,2, ..., m \qquad (12)$$

2. Linear regression analysis to determine a confidence band. In this regard, the reference line is first estimated. If the position of the j^{th} cross section taken

along the feed motion is denoted by z_j, the reference line through linear regression fitting is given by $x_j = b_x + K_x z_j$ or $y_j = b_y + K_y z_j$. The two scope estimations, K_x and K_y, are calculated as shown

$$K_x = \frac{\sum_{i=1}^{m}(z_i - \bar{z})(x_i - \bar{x})}{\sum_{i=1}^{m}(z_i - \bar{z})^2} \quad \text{and} \quad K_y = \frac{\sum_{i=1}^{m}(z_i - \bar{z})(y_i - \bar{y})}{\sum_{i=1}^{m}(z_i - \bar{z})^2} \tag{13}$$

where $\bar{z} = \frac{1}{m}\sum_{j=1}^{m} z_j$, $\bar{x} = \frac{1}{m}\sum_{j=1}^{m} x_j$, and $\bar{y} = \frac{1}{m}\sum_{j=1}^{m} y_j$

As a natural follow-up, a confidence band about the reference line can be constructed based on the variance theorem (Box, et al., 1978). The widths of the two confidence bands, under the assumption of a t-distribution, are given by

$$\text{Width}_{xj} = t_{\alpha/2} \sqrt{\left[\frac{1}{m} + \frac{(z_j - \bar{z})^2}{\sum_{j=1}^{m}(z_j - \bar{z})^2} \right] s_x^2} \tag{14}$$

$$\text{Width}_{yj} = t_{\alpha/2} \sqrt{\left[\frac{1}{m} + \frac{(z_j - \bar{z})^2}{\sum_{j=1}^{m}(z_j - \bar{z})^2} \right] s_y^2} \tag{15}$$

where s_x^2 and s_y^2 are the estimates of the variance σ_x^2 and σ_y^2 associated with the two reference line fittings, and α is the level of significance . Figure 4 illustrates the estimated reference line along the y - orientation and the corresponding confidence band. Note the displayed hourglass shape of the confidence band. This is due to the fact that the prediction accuracy, such as 95% confidence interval indicated in Fig. 4, requires large upper and lower limits for those inspection points considerably away from the mid-point, $\bar{z}$.

3. Determination of the tolerance zone of straightness.

As indicated by Eqs. (14) and (15) as well as in Fig. 4, all the inspection points are well enclosed by the two parallel lines which connect the boundary points. In this research, the width of the confidence band is used to quantify the straightness. The area within the two parallel lines is used to characterize the tolerance zone, as indicated in Fig. 4. The distance between the two parallel lines is given by

$$\text{Width}_x = \text{Max}\ \{\text{Width}_{xj},\ \text{for } j = 1,2,\ \ldots,\ m\} \qquad \text{or}$$
$$\text{Width}_y = \text{Max}\ \{\text{Width}_{yj},\ \text{for } j = 1,2,\ \ldots,\ m\}$$

Since there are two fitted reference lines along two orientations perpendicular to each other, it would be proper to use a vectorial sum of the two widths to represent the width of the tolerance zone of straightness. This distance is given by

$$\text{Width}_{TZ} = \sqrt{(\text{Width}_X)^2 + (\text{Width}_Y)^2} \qquad (16)$$

It is evident that this vectorial sum is directly related to the range given by $\{z_{max}, z_{min}\}$. Hence, a large range between z_{max} and z_{min} will cause a large natural deviation of the inspection points. This conclusion well matches observations in machining practice. When machining two similar workpieces different only in cutting length, quality control for the straightness requirement would be considerably easier when concerned with the workpiece having the short length as opposed to that of the longer length.

3. Case Study - Control of Dimensioning and Geometric Tolerancing

Assume that an in-process inspection system has been designed for monitoring a turning process, as shown in Fig. 1. Setting the control limits for this monitoring system may be considered as an example to demonstrate the applicability of this research.

Figure 5 depicts the simulation model to generate the machined surface topography for the purpose of setting these control limits. The simulation model consists of the following four modules: the input function module, the machining (turning) system module, the tool geometric motion module, and the surface topography generation module. The first two modules constitute the model of the turning process. The output of this model is the tool vibratory motion, which is integrated with the tool geometric motion to generate the numerical database for the construction of simulated surface topography. The details of these modules and the simulation process can be found in Zhang, et al. (1989).

In this demonstration example, the following parameters were used in computer simulation (Zhang and Hwang, 1990).

1.	Workpiece material:	SAE 1015
2.	Workpiece geometry:	Length x Diameter = 50 x 20 mm
3.	Tool geometry:	Nose radius = 0.8 mm and rake angle = 0^o
4.	Cutting data:	feed = 0.10 mm/rev, depth of cut = 0.6 mm
5.	Spindle Speed:	600 rpm
6.	Unit cutting force:	2000 Mpa
7.	Structural Dynamics	stiffness = $1x10^6$ N/m
	of the Lathe	damping ratio = 0.06
	(one-degree-of-freedom):	equivalent mass = 2 kg

In order to simulate the random tool motion, a stochastic model which approximates the hardness variation of the material being machined as a normal distribution is used (Zhang, 1986). As indicated in Fig. 1, this normal distribution is treated as one input function to the machining system model to simulate random variation of the instantaneous cutting force during machining. A large value of the instantaneous cutting force implies that the cutting edge is cutting a hard spot in the material. Similarly, a low value of hardness corresponds to a soft spot in the material, leading to the drop of the cutting force magnitude. The simulated random variation of the instantaneous cutting force during machining, consequently, the simulated random tool motion, quantifies the effect of the natural variation of the machining process on the evaluation of performance measures such as machining accuracy.

Through utilization of the numerical database, for example, retrieving the tool positions along one revolution of the workpiece, metrological indices such as diameter dimensioning and roundness may be calculated using Eqs. (1-8). Table 1 lists the calculated results from a polar plot similar to Fig. 2a. As indicated in Table 1, the mean value of the diameter dimensioning, $\overline{D}$ = 200.088 mm, is an average of the twenty individual diameter measurements assumably taken at different orientations. Physical interpretation of $\overline{D}$ is the dynamic setting position of the cutting tool with respect to the workpiece during machining. The standard deviation, σ_D = 0.09 mm, as listed in Table 1, provides a basis for determining the control limits for detection of tool position deviation from its dynamic setting position caused by external disturbing factors such as tool wear and heat deformation of the machine tool. The calculated roundness value, RN = 5.95 µm as listed, implies such a deviation from the ideal circumferential profile is unavoidable during machining as a result of the variabilities inherently associated with the machining process. Note that the calculated center coordinates, C_x = 0.3 µm and C_y = 0.06 µm as listed, will be used in the evaluation of the metrological index, straightness.

Table 2 lists the data used to calculate the straightness index. Note that the data presented in each row of Table 2 is associated with an individual polar plot, as shown in Fig. 2b. Pairs of x_j and y_j are the coordinates of inspection points and are calculated using Eqs. (11) and (12). Pairs of $\hat{x}_j$ and $\hat{y}_j$ are the coordinates estimated by the two fitted reference lines, respectively. The two confidence bands associated with their fitted reference lines, $Width_x$ = 6.5 µm and $Width_y$ = 5.3 µm, are calculated for the derivation of $Width_{TZ}$ = 8.39 µm, using Eq. (15). The calculation process to derive $Width_{TZ}$ to characterize the tolerance zone for the purpose of monitoring this metrological index - straightness, is illustrated in Table 2. Note that the derived $Width_{TN}$, which is equal to 8.39 µm in the present case, serves as the upper control limit during the on-line monitoring process. Since the distance between the two parallel lines which enclose all inspection points is governed by the cutting range, $\{z_{max}, z_{min}\}$, the concept of a moving average should be used. Hence, this distance may be instantaneously determined by deleting the first data entry and adding the new data entry just detected. Thus a constant cutting range during the on-line evaluation of $Width_{TZ}$ is maintained.

IV. Discussion of Results

As demonstrated by the results presented in the case study, this research combines theoretical studies and experimental work to reveal the fundamental factors related to the variation of dimensions and geometrical features formed during machining. These factors form a basis for the measurement of geometric tolerances. The identification of natural variation of dimensions and geometric features during their formation in the machining process serves as a testbed for the development of an in-process verification system through on-line monitoring of the machining process. Contributions of this research to the current knowledge of manufacturing can be further evidenced through consideration of the following three aspects.

First and foremost, the analysis of dimensioning and geometric tolerancing developed in this research captures the meaning of tolerances. Tolerances are specified in engineering drawings for the purpose of unambiguous interpretation of the designer's requirements during manufacturing. However, a more important aspect of having tolerances specified in engineering drawings is to recognize natural variations of dimensions and geometric features while they are being made. The developed methodology to integrate the random tool motion into the surface topography generation for the evaluation of metrological indices establishes a link between basic material properties, such as the hardness variability and machining performance measures, such as the dimensional accuracy during machining. This link offers the design engineer a tool to estimate the low limit when he/she is assigning default tolerances during the product design. As demonstrated in the case study, the default tolerances are governed by those variations whose occurrence during machining is unavoidable. In general, a diameter tolerance which is narrower than $6\sigma_D$, is assigned as a required specification by the design engineer. This tolerance specification will pose a manufacturability problem to the production engineer because the machining process does not have a compatible capability to meet this artificial and unreasonable specification. Therefore, the methodology developed in this research is a useful consultation tool for design engineers to properly select tolerances, effectively pushing quality control farther upstream into engineering design. Perhaps, to experts in the area of artificial intelligence, this methodology may offer them some insight in the development of a reasoning system, which functions as a manufacturability advisor to automate concurrent product design and manufacturing through a check of he design rationale for manufacturability.

Secondly, the effectiveness and uniqueness of this research in quantifying the natural variations associated with dimensions and geometric features while they are being made, may have a significant impact on quality and productivity improvement. As an example, for a given part material, cutting tool, and machine tool, the developed computer-based environment can support the decision-making process of selecting cutting parameters, such as feed, depth of cut, and cutting speed, by comparison of the simulation results with the tolerance specifications on the blue print. Such a capability meets the increasing demand in machining operation planning, especially in NC machining, where the selection of the cutting specifications has to be made during the programming stage. In fact, this research provides a mathematical mapping function between the sensing signal(s) and the geometric tolerancing specification evaluation. This represents a significant step forward to developing in-process verification quality control systems, a long term goal of computer integrated manufacturing.

Finally, this research also provides a method to perform off-line control of machining accuracy. Upon establishing a link between basic material properties and machining performance measures, such as dimensional accuracy during machining, the effect of the basic material properties, such as nonhomogeneous distribution of hardness in the material being machined, on performance measures can be quantified. As a result, control of basic material properties through heat treatment prior to the machining serves as an effective way to control and improve product quality thus resulting in accurate dimensions as well as a fine finish surface.

V. Conclusions

A quality assurance system based on in-process verification through on-line indirect measurement has been proposed in this research. For the purpose of developing such a system, natural variations associated with dimensions and geometric features formed during machining have been studied. The random tool motion due to nonhomogeneous distributions of the basic material properties in the material being machined has been incorporated in the evaluation of machining performance measures, with emphasis given to the measurement of dimensioning and geometric tolerancing. Methods to quantify the natural variation of dimensioning and geometric tolerancing are developed for the evaluation of metrological indices, such as roundness and straightness of a cylindrical surface. These methods assist the determination of the control limits designed for on-line monitoring to detect external disturbances to the normal machining process.

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Nomenclature

C_x = x-coordinate of the center related to roundness

C_y = y-coordinate of the center related to roundness

D_i = measured value of the diameter in the i^{th} orientation

D_{inner} = diameter of the smallest bounding circle

D_{outer} = diameter of the largest bounding circle

$\overline{D}$ = Mean value of the diameter dimensioning, or nominal diameter formed during machining

K_x = slope of the fitted reference line along the x-orientation

K_y = slope of the fitted reference line along the y-orientation

m = number of polar plots, or sections, taken along the z direction, or the axis of the cylindrical surface

n = number of orientations along which the diameter measurements are taken

RN = roundness of the i^{th} polar plot, numerically equal half of the difference between D_{outer} and D_{inner}

$\overline{RN}$ = mean of the roundness values evaluated from individual polar plots

s_x^2 = sample variance associated with the reference line fitting in the x-orientation

s_y^2 = sample variance associated with the reference line fitting in the y-orientation

t = parameter related to t-distribution

$Width_{TZ}$ = distance of the tolerance zone of straightness

$Width_x$ = maximum value of $Width_{xj}$ for $j = 1, 2, \ldots, m$

$Width_{xj}$ = width of the confidence band in the x - orientation at the j^{th} section

$Width_y$ = maximum value of $Width_{yj}$ for $j = 1, 2, \ldots, m$

$Width_{yj}$ = width of the confidence band in the y - orientation at the j^{th} section

x = direction in accordance with cutting speed

x_i = x-coordinate of the i^{th} tool position during machining

$\overline{x}$ = mean value of x-coordinates of the inspection points

y = direction in accordance with depth of cut

y_i = y-coordinate of the i^{th} tool position during machining

$\overline{y}$ = mean value of y-coordinates of the inspection points

z = direction in accordance with feed

z_j = coordinate of the j^{th} section along the axis of the cylindrical surface

$\overline{z}$ = mean value of z-coordinates

X_j = x-coordinate of the i^{th} inspection point

Y_j = y-coordinate of the i^{th} inspection point

α = significance level chosen in a statistical inference test

θ_i = orientation angle of the i^{th} radial vector

ρ_i = length of the i^{th} radial vector

σ_D = standard deviation of nominal diameter, $\overline{D}$ formed during machining

σ_{RN} = standard deviation of the estimated mean roundness value, $\overline{RN}$

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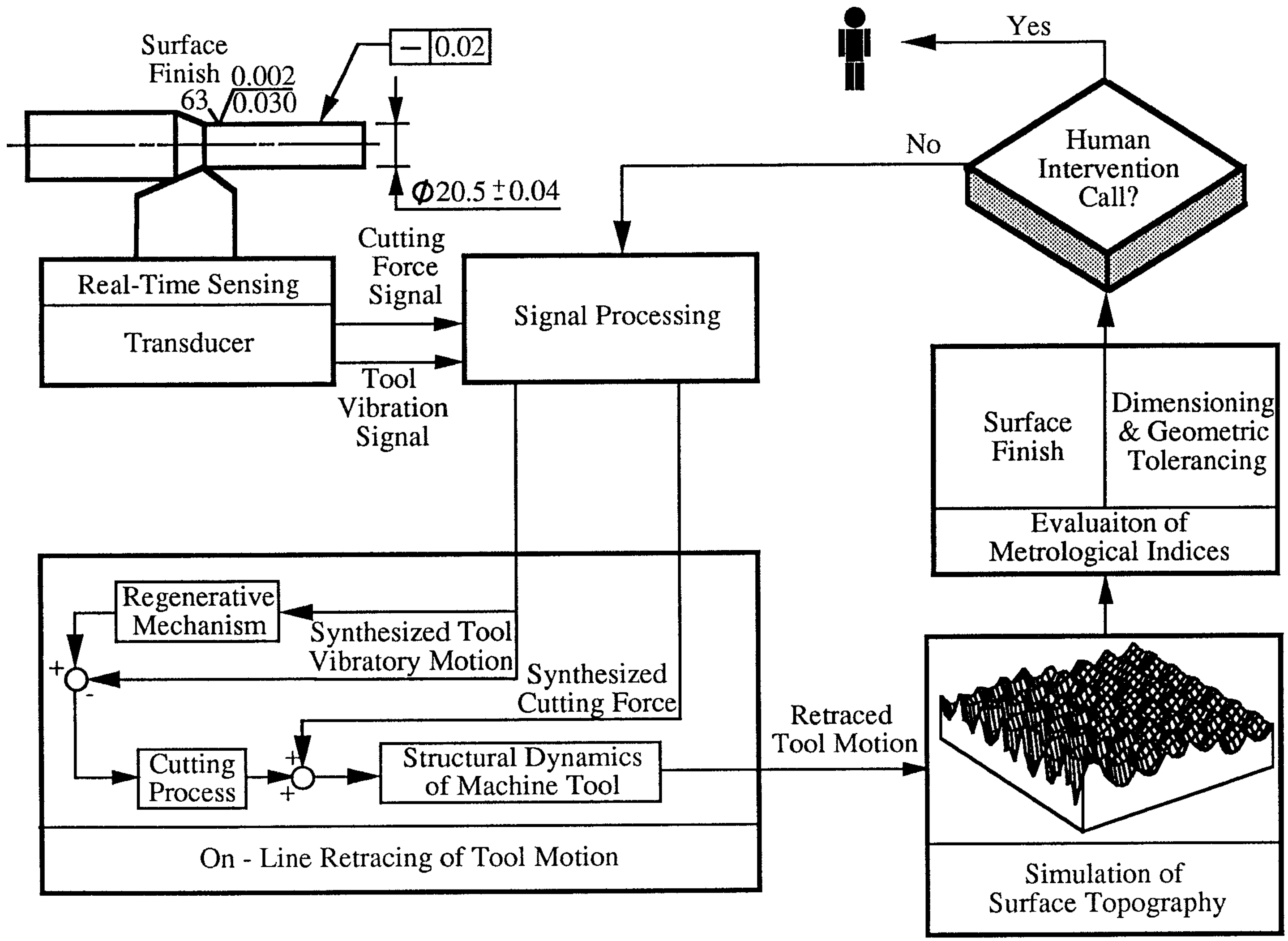
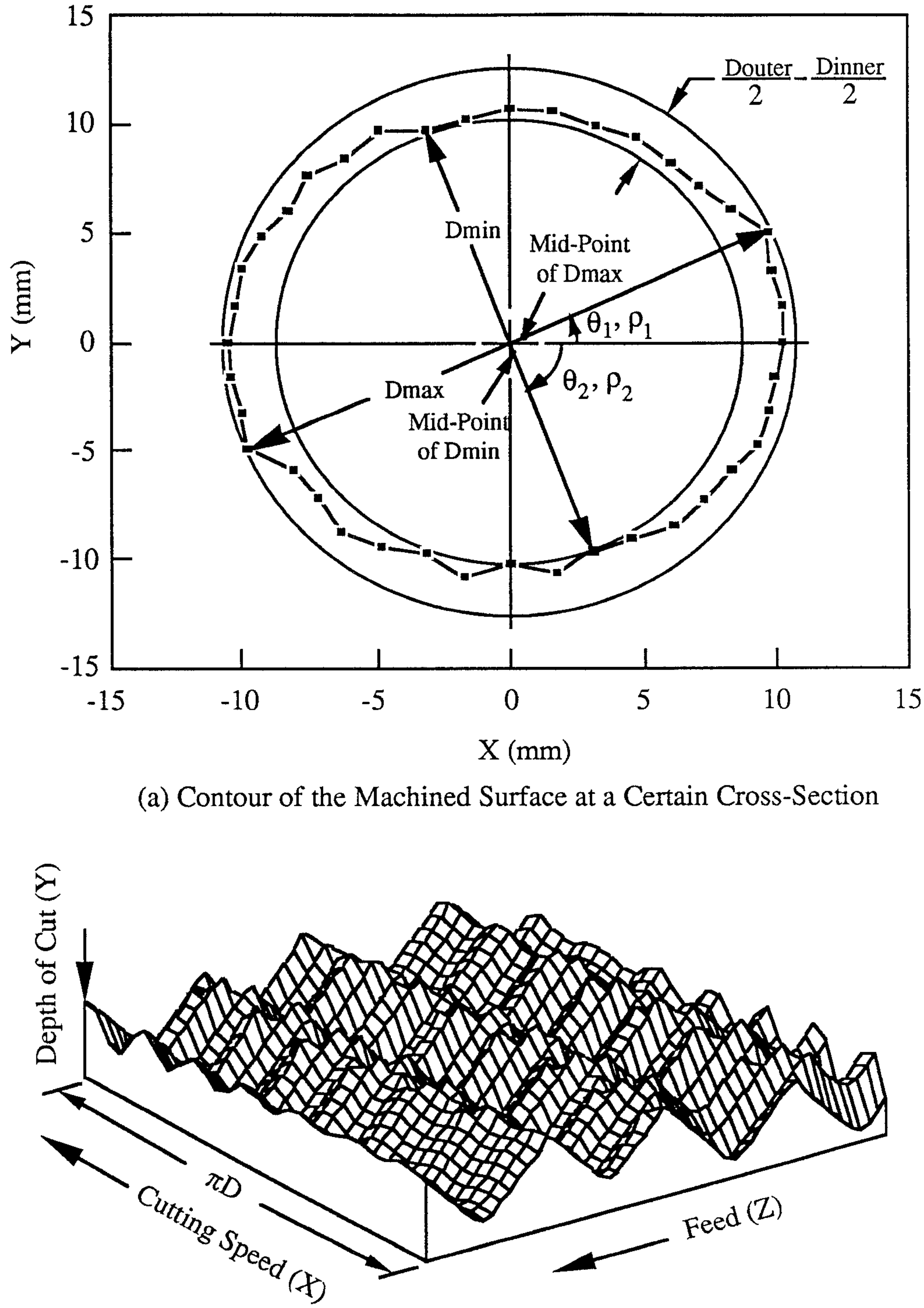


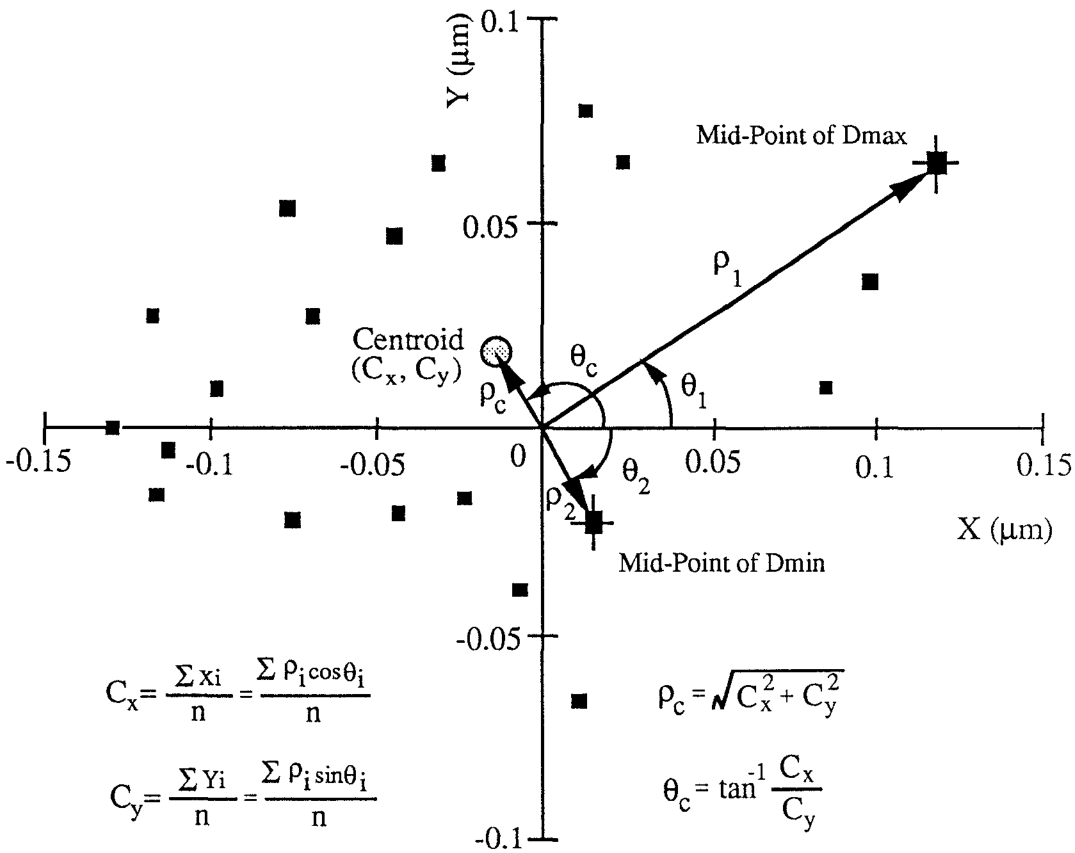
Figure 1 Outline of a General Quality Assurance System



(a) Contour of the Machined Surface at a Certain Cross-Section

(b) Simulated Surface Topography

Figure 2 Analysis of Dimensioning and Geometric Tolerancing through Surface Topography Generation



$$C_x = \frac{\Sigma x_i}{n} = \frac{\Sigma \rho_i \cos\theta_i}{n}$$

$$C_y = \frac{\Sigma Y_i}{n} = \frac{\Sigma \rho_i \sin\theta_i}{n}$$

$$\rho_c = \sqrt{C_x^2 + C_y^2}$$

$$\theta_c = \tan^{-1} \frac{C_x}{C_y}$$

Figure 3 Determination of the Centroid

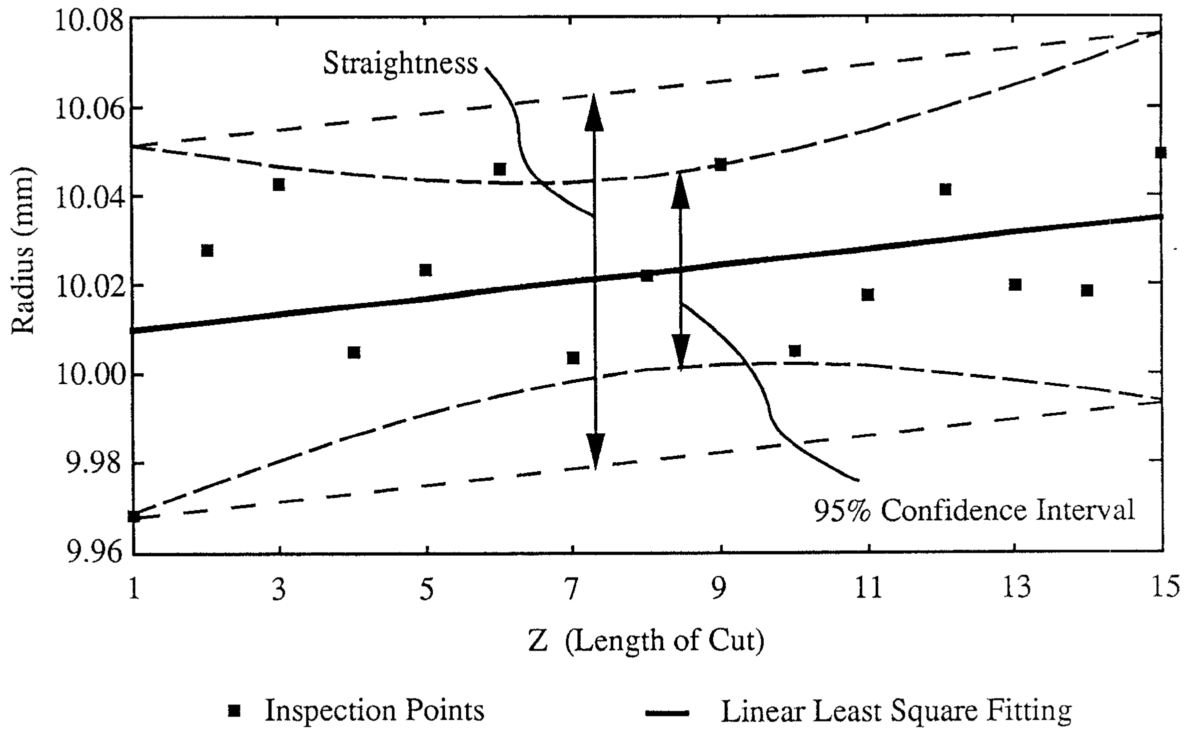


Figure 4 Straightness Estimation Based on Confidence Band

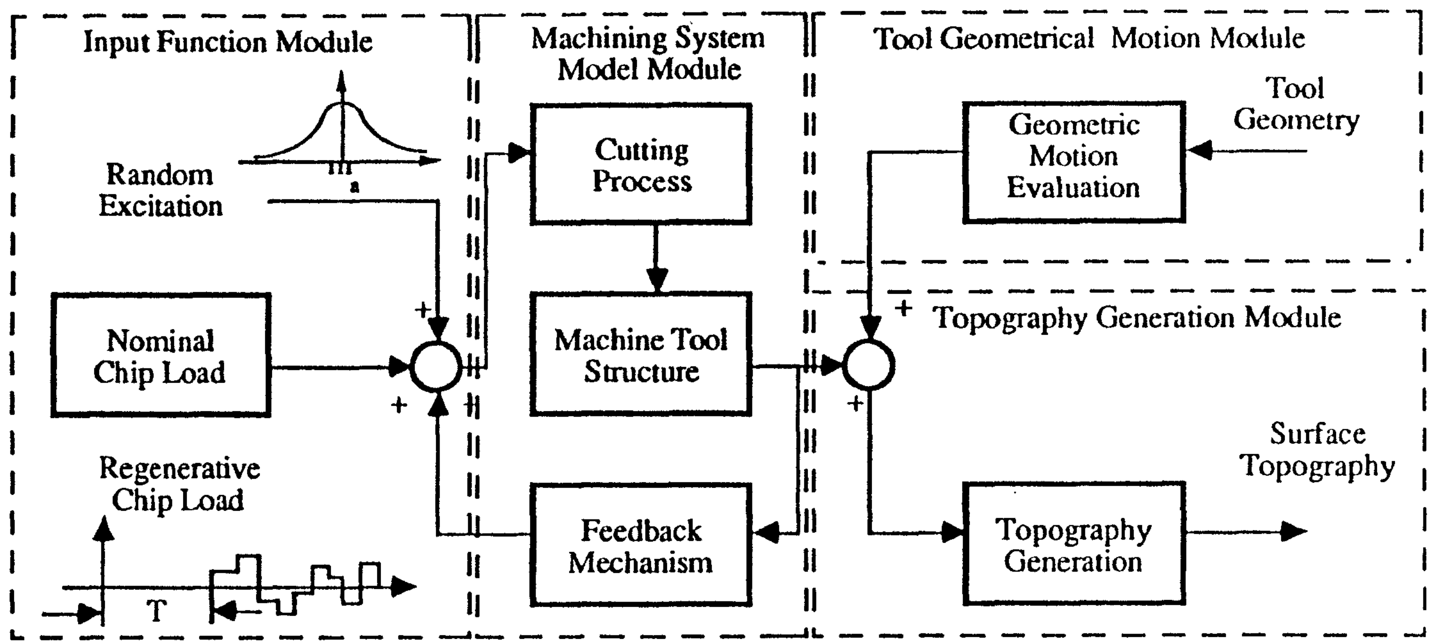


Fig. 5 Methodology to Simulate the Topography of a Machined Surface

Table 1 $\overline{D}$, σ_D, RN, C_x, and C_y Calculated from Polar Plot

Pair Index i	D_i (mm)	ρ_i (μm)	θ_i (deg)
1	20.0035	0.20619	0
2	20.0067	1.15738	9
3	20.0059	0.20459	18
4	20.0102	1.19599	27
5	20.0173	0.90266	36
6	20.0107	3.67991	45
7	20.0050	0.59535	54
8	20.0109	1.28220	63
9	20.0038	1.01515	72
10	20.0108	4.16640	81
11	20.0100	0.39854	-90
12	20.0071	0.79346	-81
13	20.0054	0.78434	-72
14	20.0092	2.21629	-63
15	20.0120	0.62186	-54
16	20.0059	1.28127	-45
17	20.0093	3.45053	-36
18	20.0073	1.49593	-27
19	20.0074	0.94832	-18
20	20.0166	1.57658	-9

D_{max} = 20.0173 mm C_x = 0.303 μm

D_{min} = 20.0035 mm C_y = 0.060 μm

$\overline{D}$ = 20.0088 mm σ_D = 9.263 μm

D_{outer} = 20.0161 mm D_{inner} = 20.0042 mm

Roundness = RN = 5.950 μm

Table 2 Data Used for Reference Line Fitting and Evaluating Straightness Index

Section Index j	Center Coordinates		Inspected Coordinates		Fitted Coordinates			
	C_{Xj} (μm)	C_{Yj} (μm)	X_j (mm)	Y_j (mm)	$\hat{X}_j$ (mm)	$\hat{Y}_j$ (mm)	$Width_{Xj}$ (μm)	$Width_{Yj}$ (μm)
1	-1.104	1.244	9.9965560	9.9989040	10.000886	10.000994	3.265	2.651
2	0.286	-0.143	10.002485	10.002056	10.001018	10.001143	2.935	2.383
3	0.303	0.060	10.004681	10.004438	10.001148	10.001292	2.623	2.130
4	-0.237	-0.616	9.9977890	9.9974100	10.001279	10.001440	2.337	1.897
5	0.325	-0.067	10.002026	10.001633	10.001410	10.001590	2.088	1.695
6	0.015	0.317	10.004066	10.004368	10.001542	10.001739	1.890	1.534
7	1.979	0.400	10.003918	10.002338	10.001673	10.001887	1.760	1.429
8	-0.165	-0.100	10.001457	10.001522	10.001803	10.002036	1.715	1.392
9	-0.275	0.288	10.005238	10.005800	10.001935	10.002186	1.760	1.429
10	-1.589	-0.487	9.9968940	9.9979950	10.002067	10.002334	1.890	1.534
11	0.166	-0.157	10.002749	10.002426	10.002197	10.002483	2.088	1.695
12	-0.086	-0.147	10.004439	10.004379	10.002328	10.002632	2.337	1.897
13	-2.357	0.184	9.9981020	10.000642	10.002459	10.002781	2.623	2.130
14	-0.347	-0.247	10.002013	10.002113	10.002591	10.002930	2.935	2.383
15	-0.016	-0.140	10.004654	10.004529	10.002722	10.003079	3.265	2.651

$K_X = 0.1311$, $K_Y = 0.1490$, $b_X = 10.000755$, $b_Y = 10.000755$, $S_X^2 = 9.0 \times 10^{-6}$, $S_Y^2 = 6.0 \times 10^{-6}$