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Straightness Measurement Technique for a Machine Tool of Moving Table Type using the Profile Matching Method
(이동테이블형 공작기계에서의 형상중첩법을 이용한 진직도 측정기술)

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[1]Abstract

The straightness property is one of fundamental geometric tolerances to be strictly controlled for guideways of machine tools and measuring machines. The straightness measurement for long guideways was usually difficult to perform, and it needed additional equipments or special treatment with limited application.
In this paper, a new approach is proposed using the profile matching technique for the long guideways, which can be applicable to most of straightness measurements. An edge of relatively short length is located along a divided section of a long guideway, and the local straightness measurement is performed. The edge is then moved to the next section with several points overlap. After the local straightness profile is measured for every section along the long guideway with overlap, the global straightness profile is constructed using the profile matching technique based on the least squares method. The proposed technique is numerically tested for two cases of known global straightness profile arc profile and irregular profile, and those profiles with and without random error intervention, respectively. When no random errors are involved, the constructed global profile is identical to the original profile. When the random errors are involved, the effect of the number of overlap points are investigated, and it is also found that the difference between the constructed and original profiles is very close to the limit of random uncertainty with just few overlap points. The developed technique has been practically applied to a vertical milling machine of moving table type, and showed good performance. Thus the accuracy and efficiency of the proposed method are demonstrated, and shows great potential for variety of application for most of straightness measurement cases using straight edges, laser optics, and angular measurement equipments.

Keywords: Straightness Measurement, Guideways, Straight Edges, Profile Matching, Least Squares Method

1. Introduction

The straightness tolerance is one of fundamental geometric tolerances to be strictly controlled for guideways of machine tools and measuring machines. Several methods have been usually used for the straightness measurement: laser interferometer with straightness optics, straight edge with displacement sensors such as LVDT(linear variable displacement transducer) and gap sensor, and incremental angular measurement using autocollimator or angular measurement optics, etc[1,2]. In the method using the straight edge linear displacement sensor measures the deviation between the guideway and the edge, and it can give accurate straightness profile when combined with the reversal technique for removing errors of the reference edge[1,2]. For long guideways, however, the long straight edge was hardly used, and it was because the required long straight edge is usually difficult to manufacture and is prone to deformation due to gravity. Burdekin[1] mentioned a overlap technique performing angle measurement, in which a long guideway is divided into several sections, and the local straightness is measured with a short edge along each section. Angle measurement is also performed using a precision level at each edge setup, then it is combined to give the global straightness profile for the long guideway. The overlap technique with angle measurement, however, has been also limited to the vertical straightness measurement along horizontal axis for a long guideway due to the limited direction of the level operation. In this paper, a new approach is proposed using the profile matching technique for the long guideways, which can be applicable to vertical and horizontal straightness measurement without performing angular measurement. An edge of relatively short length is located along a divided section of a long guideway, and the local straightness measurement is performed. The edge is then moved to the next section with several points overlap. After the local straightness profile is measured for every section along the long guideway, the global straightness profile is constructed using the profile matching technique based on the least straightness method. The proposed technique is numerically tested for two cases of known global straightnesss profiles arc profile and irregular profile, and those profiles with and without random error intervention, respectively. When no random errors are involved, the constructed global profile is identical to the original profile. When the random errors are involved, the effect of the number of overlap points are investigated, and it is also found that the difference between the constructed and original profiles is very close to the limit of random uncertainty with just few overlap points. Thus the accuracy and efficiency of the proposed method are demonstrated and shows great potential for variety of application for most of straightnesss measurement of long guideways with laser optics and angular measurement equipments.

2 Straightness Measurement Technique using Straight Edges

Straight edges are usually made of steel, granite, and the edge surfaces are used as the reference surface for straightness measurement, where the straightness error can be evaluated by a comparison between a machine axis and the reference surface. The straightness profile of a reference straight edge is also to be measured and can be compensated for precise straightness measurement. The reversal technique is generally used for evaluation of the straightness profile of the reference surface [2]

2.1 Reversal Technique

Let X be a nominal position along an edge and the straightness profile of a machine axis is to measured. S(X), Y(X) are the straightness profile along the edge and the machine axis, respectively. When the measurement setup is as in the left hand side of fig.1, the measured profile would be the difference S(X)-Y(X), when the edge is reversed as in the right hand side of fig 1, the measured profile would be the difference -S(X)-Y(X). Thus the edge straightness profile S(X), and the straightness profile of machine axis, Y(X), can be evaluated. That is,

Forward measurement profile = S(X) - Y(X)
Reverse measurement profile = -S(X) - Y(X)

Thus
Y(X) = - (Forward Measurement Profile + Reverse Measurement Profile) / 2 (1)

S(X) = (Forward Measurement - Reverse Measurement Profile) / 2 (2)

Therefore the straightness profile of the edge and the machine axis can be evaluated simultaneously, and the edge profile is stored and used for profile compensation for accurate straightness measurement.

2.2 Straightness Evaluation Methods

After the straightness profiles are measured, appropriate straightness evaluation methods are to be applied. There are several ways for evaluation of straightness tolerance, and currently 3 methods are implemented in this system: end points straightness, least squares straightness, and minimum zone straightness.
Since the straightness profile is expressed in terms of the deviation of a given profile from a reference straight line, the measured profile is adjusted to give the straightness profile.
Let Y_i be a global profile, and δY_i be a straightness profile at X position, the straightness profile, δY_i, can be evaluated as

$$\delta Y_i = Y_i - AX_i \tag{3}$$

and straightness tolerance, ST, is

$$ST = \max(\delta Y_i) - \min(\delta Y_i) \tag{4}$$

where A is a best fit slope of the reference straight line for the measured profile, and currently 3 methods such as end points fit, least squares fit, and minimum zone fit are widely used.

End Points Fit

The constant A of eq(3) can be evaluated from a reference straight line passing the two end points of the measured profile. That is,

$$A= (Y_M - Y_1)/(X_M - X_1) \tag{5}$$

where (X_1, Y_1), (X_M, Y_M) are the end point data of the measured profile respectively.

Least Squares Fit

The constant A of eq(3) can be evaluated using the least squares technique, and the constant, A, is,

$$A= \left(N \sum_{j=1}^{N} X_i Y_i - \sum_{j=1}^{N} X_i \sum_{j=1}^{N} Y_i\right) / \left(N \sum_{j=1}^{N} Y_i^2 - \left(\sum_{j=1}^{N} X_i\right)^2\right) \tag{6}$$

where N is the total number of data points on the measured profile

Minimum Zone Fit

The constant A can be determined so that the straightness tolerance eq(4) is minimum, and there are several methods for minimum zone fit. A graphical solution can be given if three enclosing points, P1,P2,P3 are found with alternate signs.[3]

$$A= (Y_{p3} - Y_{p1}) / (X_{p3} - X_{p1}) \tag{7}$$

Therefore the straightness profile and the straightness tolerance can be evaluated from eq(3),(4).

3. Profile Matching Technique for Straightness Profile

3.1 Concept of Profile Matching

The concept of profile matching for straightness measurement can be explained as follows. Consider a long guideway of arc profile for the span length, L, as in fig.2, where the global straightness profile is to be measured. In order to measure the global straightness profile, the guideway can be divided into three local sections, OAB, ABC, BCD, whose length is l, allowing local overlap. Assume AB is the overlap region between the OAB and ABC local sections, and BC is the overlap region between the ABC and BCD local sections. When the straightness profile is measured along the OAB section with a straightedge of length, l, the measured local straightness profile is like OAB profile in the second figure of fig.2. Similarly, when the straightness profile is measured for ABC local section, the measured local straightness profile is like ABC profile in the second figure of fig.2. The overlap region, AB, is the physically identical region in the guideway, and thus the AB region must show the identical profile. Therefore the profile of ABC local section can be transformed such that the AB region of OAB section and AB region of ABC section can be matched. A best profile matching method can be designed such that the AB region of OAB section and AB region of the ABC section can be matched. Thus the global profile OABC can be constructed as in the third figure of fig.2. Similarly, the local profile BCD can be transformed such that the overlap BC region can be matched with that of ABC profile, and the global profile OABCD can be constructed.

In this paper, the profile matching technique based on the least squares method is proposed, and detail description is given as follows.

3.2 Least Squares Method

In the fig.3a, consider a straight edge located at Oi position (i=1,2,3..) along the guideway, and define a local coordinate system, $O_iX_iY_i$, where O_iX_i indicates a direction parallel to the edge surface and Y_i indicates a local straightness profile. When the edge is moved to the next position O_{i+1}, the local profile is similarly defined as Y_{i+1}, and the overlap region can be defined as in fig.3b. The profile matching can be performed from the data on the overlap region.

Let $Y_{i,k}$, $Y_{i+1,k}$ (k=1,2..N) be the k'th point data on the overlap region of Y_i, Y_{i+1} profiles, respectively. As the straightness profiles are physically identical for the overlap region, the differences in the profiles on the overlap region are simply due to the differences in the setup of the edge at the O_i, O_{i+1} position, respectively.

Thus,

$$Y_{i,k} - Y_{i+1,k} = A_i X_k + B_i \qquad (8)$$

for k=1,2..N

where A_i, B_i are coefficients for defining the slope and offset of the edge at the i+1 location, and X_k is the distance from the beginning point to the kth point on the overlap region. The A_i, B_i coefficients can be evaluated based on the least squares technique as follows.

The sum of squares, E_i, between the Y_i and Y_{i+1} profiles in the overlap region, is

$$E_i = \sum_{k=1}^{N} (Y_{i,k} - Y_{i+1,k} - A_i X_k - B_i)^2 \qquad (9)$$

Applying variational principle, and assigning $\partial E_i/\partial A_i = 0$, $\partial E_i/\partial B_i = 0$,

$$A_i \sum_{k=1}^{N} X_k^2 + B_i \sum_{k=1}^{N} X_k = \sum X_k (Y_{i,k} - Y_{i+1,k}) \qquad (10)$$

$$A_i \sum_{k=1}^{N} X_k + B_i N = \sum (Y_{i,k} - Y_{i+1,k}) \qquad (11)$$

Therefore the coefficients, A_i, B_i can be calculated from eq(10),(11), that is,

$$A_i = \left(N \sum_{k=1}^{N} X_k (Y_{i,k} - Y_{i+1,k}) - \sum_{k=1}^{N} X_k \sum_{k=1}^{N} (Y_{i,k} - Y_{i+1,k})\right) / \left(N \sum_{k=1}^{N} X_k^2 - \left(\sum_{k=1}^{N} X_k\right)^2\right) \qquad (12)$$

$$B_i = \left(\sum_{k=1}^{N} X_k^2 \sum_{k=1}^{N} (Y_{i,k} - Y_{i+1,k}) - \sum_{k=1}^{N} X_k (Y_{i,k} - Y_{i+1,k}) \sum_{k=1}^{N} X_k\right) / \left(N \sum_{k=1}^{N} X_k^2 - \left(\sum_{k=1}^{N} X_k\right)^2\right) \qquad (13)$$

Thus the coefficients, A_i, B_i can be evaluated, and the relationship between the profiles Y_i and Y_{i+1} is constructed. From eq(8) the converted profile (conversion from Y_{i+1} to Y_i), CY_{i+1}, is

$$CY_{i+1} = Y_{i+1} + A_i X + B_i \qquad (14)$$

where X is the distance from the O_{i+1}.

As the Y_{i+1} profile is converted to the Y_i profile in the form of CY_{i+1}, the augmented Y_i profile, AY_i, can be constructed as the sum of existing profile Y_i and the converted profile CY_{i+1}. Thus,

$$AY_i = Y_i + CY_{i+1} \qquad (15)$$
for $i=1,2,3\ldots$

Eq(14) and (15) provide useful relationship for the profile matching. In this way, every local profile can be converted to the previous local profile, and thus transformed down to the first local profile.
After all local profiles are transformed to the first local profile, that is, global coordinate system, appropriate straightness evaluation methods can be applied for the straightness profile evaluation.

4. Straightness Measurement Simulation

In order to test the proposed straightness measurement technique using the profile matching, two known straightness profiles are used: arc profile and irregular profile. The known global profiles are divided into several local sections, and the local profiles are simulated from the global profiles. For the local profile data, the proposed profile matching technique is used, and the global profiles are reconstructed from the local profiles. The reconstructed profiles are then compared with the original global profiles. Random scattering is added to the local profiles, and it is to simulate random errors in the practical measurement procedures. The effect of size of overlap region is also considered in terms of the number of data points on the overlap region, and the deviation between the original and the reconstructed profile is observed as the number of overlap points changes.

Arc Profile of Straightness

A concave straightness profile of 10um magnitude over 1200mm length is considered for practical application, and the profile is divided into several local profiles. The local profiles are then combined to give the global straightness profile, using the proposed profile matching technique. In order to simulate the practical measurement cases, random errors of 0.1um maximum magnitude (which is typical for conventional mechanical measurement) are added to the local profiles. The local profiles with random error disturbance are then combined to give the global profile using the profile matching technique, and the effect of size of overlap region is also investigated.
When no random errors are involved, the reconstructed profiles are found as identical to the original profiles. Fig.4a shows the local arc profiles, where 0.1 um random errors are intervened, and 4 points are considered for the overlap region. Fig.4b shows the reconstructed and original profiles, demonstrating very good closeness between the two profiles in case of the random error intervention.
In order to investigate the effect of overlap size, 30 independent measurement sets are simulated for the local arc profiles with varying random error distribution, and they are combined to give corresponding global profiles with allowing various number of data points on the overlap region. The maximum deviation between the original profile and reconstructed profile is recorded for the number of overlap points. The mean deviation between the profiles is also recorded for the number of overlap points. Fig.5 shows the maximum and mean deviation when the number of overlap points is 2,3,4,5, 6 and 7. The maximum deviation approaches to 0.2 um, and the mean deviation approaches to about 0.06 um when the number of overlap points is 4 or more. In case of three overlap points, the maximum deviation is about 0.4um, and the mean deviation is about 0.07 um thus it is considered reasonably acceptable for most of conventional mechanical measurement cases.

Irregular Profile of Straightness

An irregular profile of 10 um over 1200mm length is also considered for simulation.
The divided local profiles are simulated from the global profile, and the identical reconstructed profile is obtained using the proposed profile matching technique. When no random errors are involved, the reconstructed profiles are found identical to the original profiles.
In order to simulate the practical measurement cases, random errors of 0.1um maximum magnitude (which is typical for conventional mechanical measurement) are added to the local profiles. The local profiles with random error disturbance are then combined to give the global profile using the profile matching technique, and the effect of size of overlap region is also investigated. Fig.6a shows the local irregular profiles, where 0.1um random errors are intervened. Fig.6b shows the reconstructed and roiginal profiles, demonstrating negligible deviation between the profiles for the case of 4 points overlap.
In order to investigate the effect of overlap size, 30 independent measurement sets are simulated for the local irregular profiles of with varying random error distribution, and they are combined to give corresponding global profiles with allowing various number of data points on the overlap region. The maximum deviation between the original profile and reconstructed profile is recorded for the number of overlap points. The mean deviation between the profiles is also recorded for the number of overlap points. Fig.7 shows the maximum and mean deviation between the original and reconstructed profiles when the number of overlap points is 2,3,4,5,6, and 7. The maximum deviation approaches to about 0.2 um, and the mean deviation approaches to about 0.06 um as the number of overlap points is 3 or more.

The observed facts from the fig.5,7 are:(1) The case of two overlap points is theoretically possible, but it gives big errors in practical measurement situation.(2) The case of three overlap points is considered reasonably acceptable, and thus can be used for most of conventional mechanical straightness measurement. (3) In case of four or more overlap points, the maximum and mean deviation approaches near to the random uncertainty limit, thus it is considered fully acceptable.

5. Practical Application to a machine tool of moving table type

The developed method has been applied to a practical machine tool of moving table type, where the horizontal straightness errors are to be evaluated. In order to perform accurate measurement, the straight edge was calibrated using the reversal technique. Fig.8 shows the straightness measurement data and the analysed straightness profile of the edge and the machine table. The calibrated straightness data was stored in a computer and the local profile measurement has been performed. The length of local profile was 120mm (13 steps at 10mm unit step), and the length of the global profile was 450mm(46 steps). The local profile was calculated as the measured profile minus the edge profile, after elliminating any misalignment of the edge with respect to the machine table. Fig.9 shows the local profile, and the global profile was generated from the local profiles using the proposed technique. Fig.10 shows the reconstructed global straightness profile and the original global profile, which shows that the reconstructed profile gives very close profile to the original profile. Therefore the proposed technique was verified with the experimental work, and the deviation between the two profile was observed mainly due to the accumulation of the error at the time of local profile measurement.

6. Conclusions

(1) An efficient method for straightness measurement is proposed, using the profile matching technique based on the least squares method for the overlap regions of local straightness profiles. The proposed method is found useful for the global straightness evaluation when local straightness profiles are measured, and the accuracy and efficiency are demonstrated from numerical simulation for straightness measurement data.

(2) From the numerical simulation of random error scattering, a general trend is found that the reconstructed profile is very much close to the original profile when the number of data points in the overlap regions increases. The case of three overlap points is considered reasonably acceptable, and thus can be used for most of conventional mechanical straightness measurement.

(3)The proposed technique can be applied for most of straightness measurement situations using the straight edge, laser interferometer, and angle measurement equipments, etc. Therefore the global straightness profile can be obtained for the long object by the proposed technique, using local straightness profiles measured by equipments of relatively short working range.

(4) The developed method has been practically applied to a CNC milling machine of moving table type, and showed very close value to the original straightness profile of the moving table. Thus the efficiency and the proposed technique has been demonstrated.

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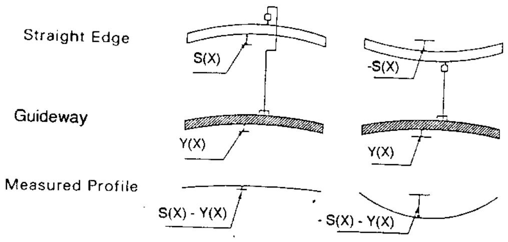


Fig.1 Reversal Technique

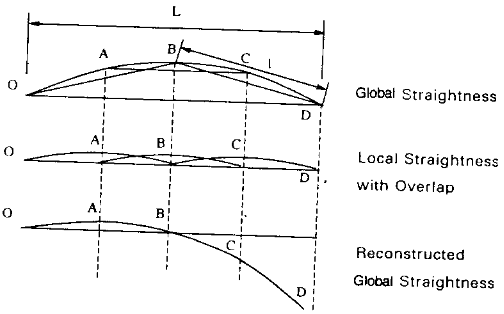


Fig.2 Concept of Profile Matching for Straightness Profile

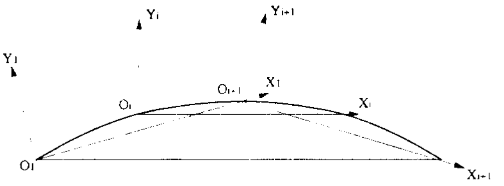


Fig.3a Global and Local Coordinate System

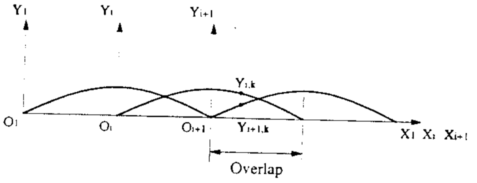


Fig.3b Measured Profile in the Local Coordinate System

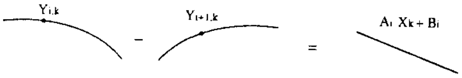


Fig.3c Profile Matching on the Ovelap Region

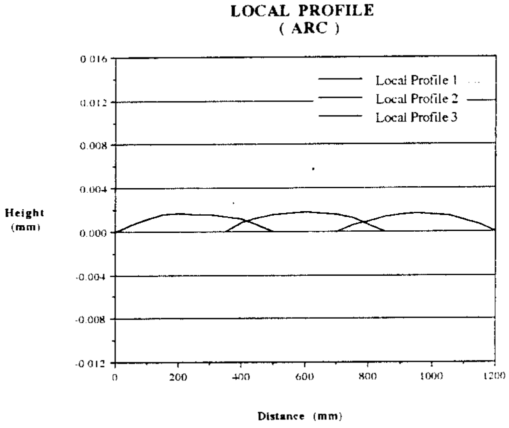


Fig 4a Local Arc Profiles in Case of Random Error Intervention

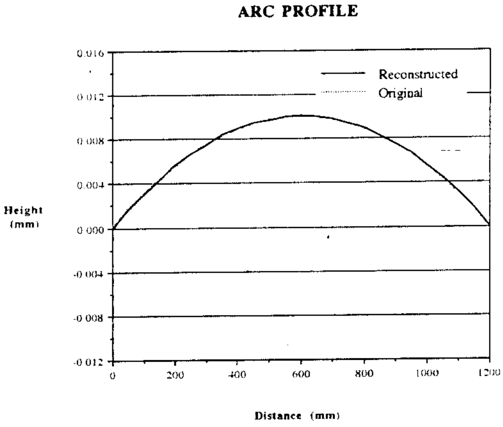


Fig.4b Original and Reconstructed Arc Profile

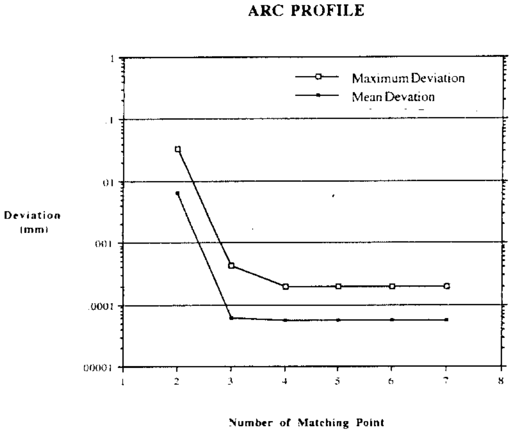


Fig.5 Maximum and Mean Deviation vs Number of Overlap Points for Arc Profile

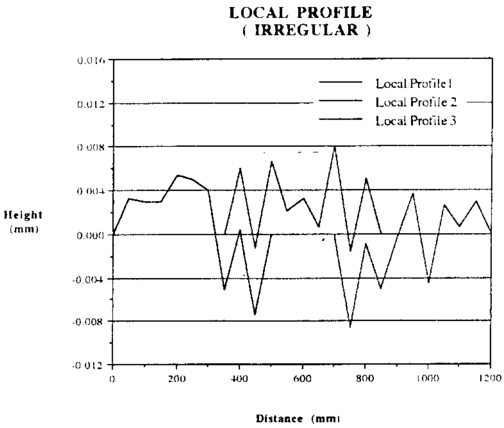


Fig.6a Local Irregular Profiles in Case of Random Error Intervention

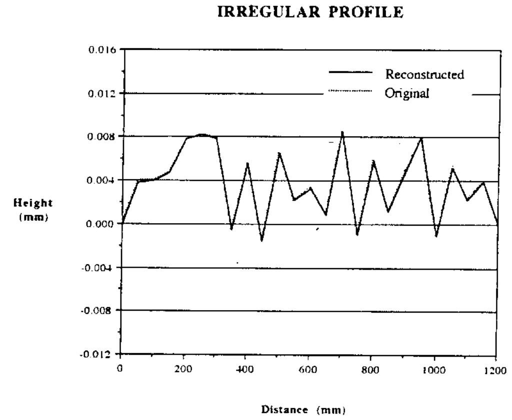


Fig.6b Original and Reconstructed Irregular Profile

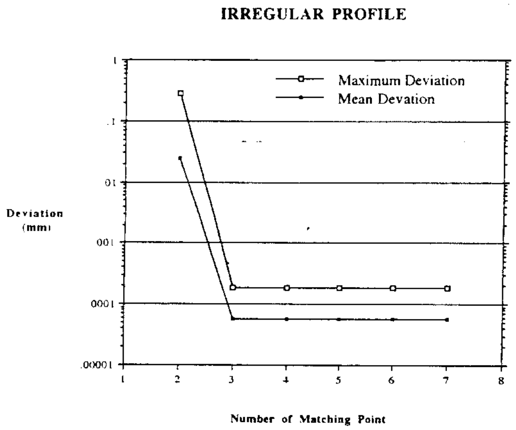
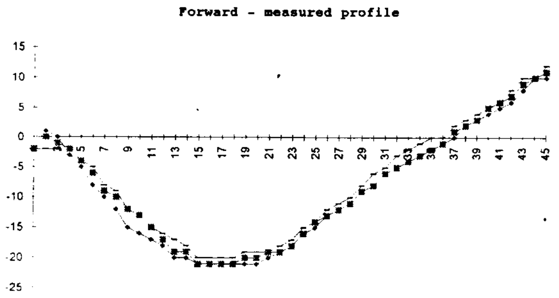


Fig.7 Maximum and Mean Deviation vs Number of Overlap Points for Irregular Profile



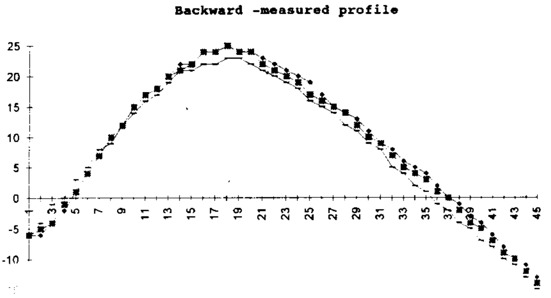


Fig.8aStraightness measured data

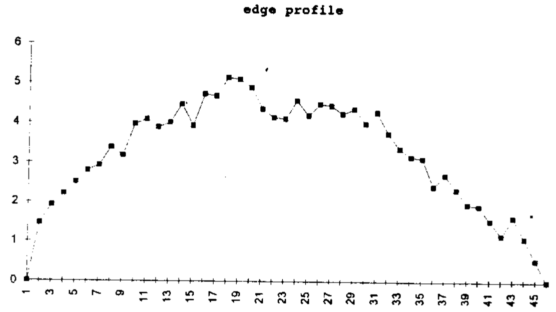


Fig.8b Edge Profile

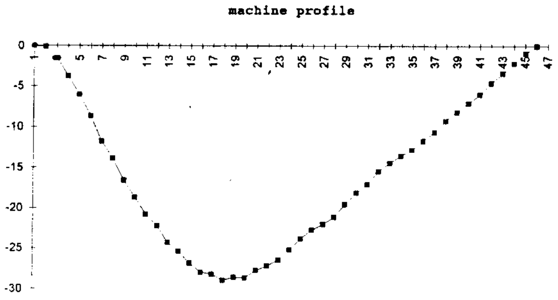


Fig.8c Machine Profile (Original)

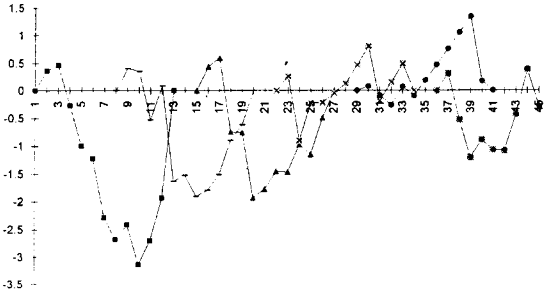


Fig.9 Local Straightness profiles

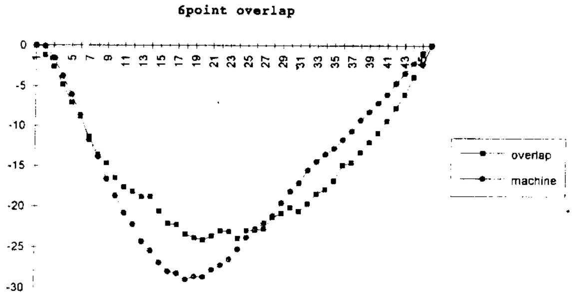


Fig 10 Reconstructed Profile and Original Profile

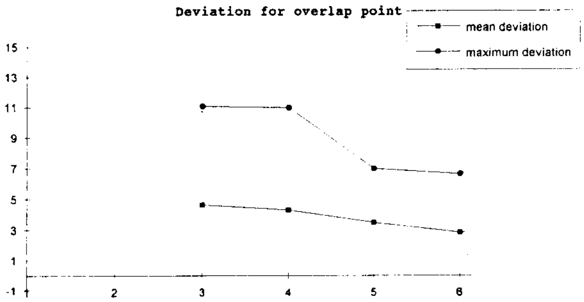


Fig 11 Maximum and Mean Deviation vs Number of Overlap Point