STUDY OF CYCLIC ERRORS IN THE COORDINATE MEASURING MACHINES

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Abstract. *The purpose of this work is to study new evaluation methods of the cyclic errors in Coordinate Measuring Machines (CMMs). In order to achieve this objective, a measuring procedure of cyclic errors and application of Fourier Analysis to the testing data were accomplished. Measurements of distances between consecutive lines of the scale were also obtained and the results have shown the existent manufacturing errors and suggested frequencies and period of errors of electronic division. After data analysis one can conclude that some times cyclic errors can be hidden and at other times wrongly evaluated. The determination of the period of the cyclic errors makes possible the use of strategies to minimize cyclic effects during measurements and positioning error calibration. A cyclic period of four millimeters was confirmed in the low frequency tests and a comparison of the cyclic errors influence during calibration of the positioning errors with and without a compensation strategy was made and results have shown that the standard deviation decreases approximately sixty-five per cent.*

Keywords. *cyclic errors, coordinate measuring machines, Moiré fringes.*

1. Introduction

Coordinate Measuring Machines (CMMs) are probably one of the most powerful metrological instruments used in the modern industry (Ni, 1995). They present simplicity during operation, flexibility, accuracy and allow the measurement of complex structures with high precision very fast, as well as, the simultaneous control of several metrological characteristics of a workpiece (Kunzmann and Wäldele, 1988).

The project and manufacturing technologies of Coordinate Measuring Machines has been largely developed since its creation, in 1954. However, one can say that it is impossible to manufacture equipments free from geometric errors, thermal errors, dynamic errors and mainly those directly related to the scales. To guarantee the accuracy and repeatability of the accomplished measurements it is necessary the knowledge of such errors, especially the cyclic errors.

The knowledge of the cyclic errors is very important because frequently the cyclic component has a larger effect in the systematic parcel ending up interfering in the quality of the obtained results in the measurement of workpieces and of the positioning error. So a specific strategy for a data collection is needed to minimize the cyclic effect.

Facing all those facts and in spite of the CMMs errors had been studied broadly, still today, the cyclic errors measurement did not receive an appropriate scientific treatment, that is, a systematic study and observation was not accomplished to permit an exact measure of its influence on coordinate measurements.

To cope with the urgent need and to contribute in the search for new evaluation methods of cyclic errors, this work shows the development and the application of a methodology that it is capable to evaluate the cyclic error in nowadays-manufactured CMMs.

2. A overview on cyclic errors and their influences in measuring accuracy

Errors presented in CMMs can be classified according to the behavior as random and systematic. The random errors occur when non-controlled external and internal influences cause non-repeatable errors. Usually, the analysis of the random errors reveals a Normal or Gaussian distribution and, therefore, they can be analyzed statistically (Slocum, 1992). Systematic errors are those that can be reproduced in magnitude when experimental conditions were held constant. They are basically subdivided into three categories: cyclic errors, progressive errors and hysteresis. Cyclic error is any error component that repeats itself at least once along an axis of the machine (Hemingray et al, 1971 and Di

Giacomo, 1986). The progressive error is the non-cyclic error component and can be positively or negatively progressive. The hysteresis is defined as the value of the difference between the average of the error for the forward and the reverse motion measured at the same target position at each measuring position (Hemingray et al, 1971 and Di Giacomo, 1986).

ASME (1997) specifies periodic error as an error present in the linear displacement of a machine that is cyclic on a certain interval, which normally coincides with the natural period of the machine scales.

Very few papers have been published in which the objective was the evaluation of the characteristics, magnitudes and sources of the cyclic error, and ways of to minimizing their effects. Analyzing the published works on cyclic errors one can notice that they have been mostly addressed to the study of pitch errors in the leadscrews of machine tools.

The design of the leadscrew and its manufacture are important factors in determining the performance and accuracy of machine tools (Butterworth, 1984). In a leadscrew driven machine with rotary encoders, the periodic error is usually synchronous with the pitch of the leadscrew, which is a convolution of the cyclic error present in leads and in encoders (ASME, 1997).

In agreement with Yamamoto and Otsuka (1970) the leadscrews used on machines tools need to be grounded, aiming high pitch accuracy. According to them, one of the causes of pitch error in grounded leadscrews is the pitch error present in the screw of the thread grinding machine.

Ioshimoto (1979) compared the pitch error and the position tolerance through a multi-holes pattern and it ended, in this case, that a narrow correlation exists between the positioning error and the cyclic error.

Butterworth and Burdekin (1987) proposed a method for on-the-fly measurement of the axial displacement of lathe and thread grinder carriages in screw generating operation mode. They concluded that the twelve-sided polygon used during evaluation was sufficient to assess the periodic errors and they suggested the use of a polygon with 36 sides if a more detailed analysis of the periodic waveform would be desirable.

Burdekin and Voutsadopoulos (1982) state that the cyclic errors are evident in most modern length and rotation measuring transducer systems. They suggest that cyclic errors should receive individual treatment with use of computational programs and separate experimental procedures, avoiding the combination with other systematic errors. According to Tlusty and Koenigsberger (1970), this separate measurement should be made in small steps over short distances.

Therefore, the study of the cyclic errors in CMMs can be said to be an up-to-date theme due to the little availability of works in the area and absence of suggestion for cyclic error compensation.

The positioning reading system of CMMs uses optical scales properly placed at each one of the three guideways. These scales use the principle of Moiré fringes that consists of an optoelectronic system composed of light source, moving scale, fixed scale and photocells. The relative displacement between fixed and moving scales provides a intensity light variation in the photocells measured by the number of Moiré fringes passing through a datum and interpreted as displacement.

The accuracy of the measuring system of a CMM mainly depends on the quality of the scale tape and the scale graduation. The graduation depends on the accuracy and width of the lines, quality of the line edges, on the density and the size of imperfections and also the homogeneity of the optical characteristics such as degrees of reflection, transmission and absorption.

The cyclic errors, differently from the geometric errors and the thermally induced errors, have a significant influence in measuring results on a very small displacement hindering most of the measuring tasks. The limited accuracy of the manufacturing methods of scales is one of the main factors responsible by the cyclic errors. CMMs use scales drawn and manufactured by photographic methods or marked in step and repeat machines. In both methods the distances between succeeding lines are prone to systematic errors and therefore, with the increasing of the number of lines, systematic errors are added up. During manufacturing, error compensation is provided when the amount of errors reaches a predetermined value. The error correction made at predetermined lengths defines a period which one can call the low frequency cyclic error. This process must be repeated all along the scale. Another factor that contributes to the existence of cyclic errors originates from high resolution required by CMM that goes beyond the existent scales manufacturing capabilities.

This problem is somewhat solved by means of electronic splitting up. The electronic sign obtained as two consecutive lines on the scale can be associated to a sine signal generated by Moiré fringes. Digital conversion and electronic division of these signals also generate periodic errors and can be called high frequency cyclic error.

It can be observed in the measuring machines the presence two types of cyclic errors. The first type, due to the manufacturing process, denominated low frequency cyclic error, and the ones caused by the electronic subdivision called high frequency cyclic error.

3. Experimental procedures, results and discussions

The necessary experiments to evaluate the cyclic errors were carried out in a moving bridge type CMM, in the Machine Tools Laboratory of Escola de Engenharia de São Carlos - USP. The used instrument to determine the cyclic error was a laser interferometer, Fig. (1).

Figure 1. CMM and laser interferometer measuring system.

The study of the cyclic errors here presented was divided in four parts: data acquisition of low frequency cyclic error, Fast Fourier Transform analysis, conventional measurement of the spacing between lines and cyclic influence in the positioning error, Fig. (1).

3.1 Data acquisition of low frequency cyclic error

During data acquisition of low frequency cyclic errors, pulses of the machine encoder has been used as positioning reference giving to the system the capacity of the on-the-fly measurements execution, in which the machine does not need to stop and measurement is taken when passing through a predetermined position.

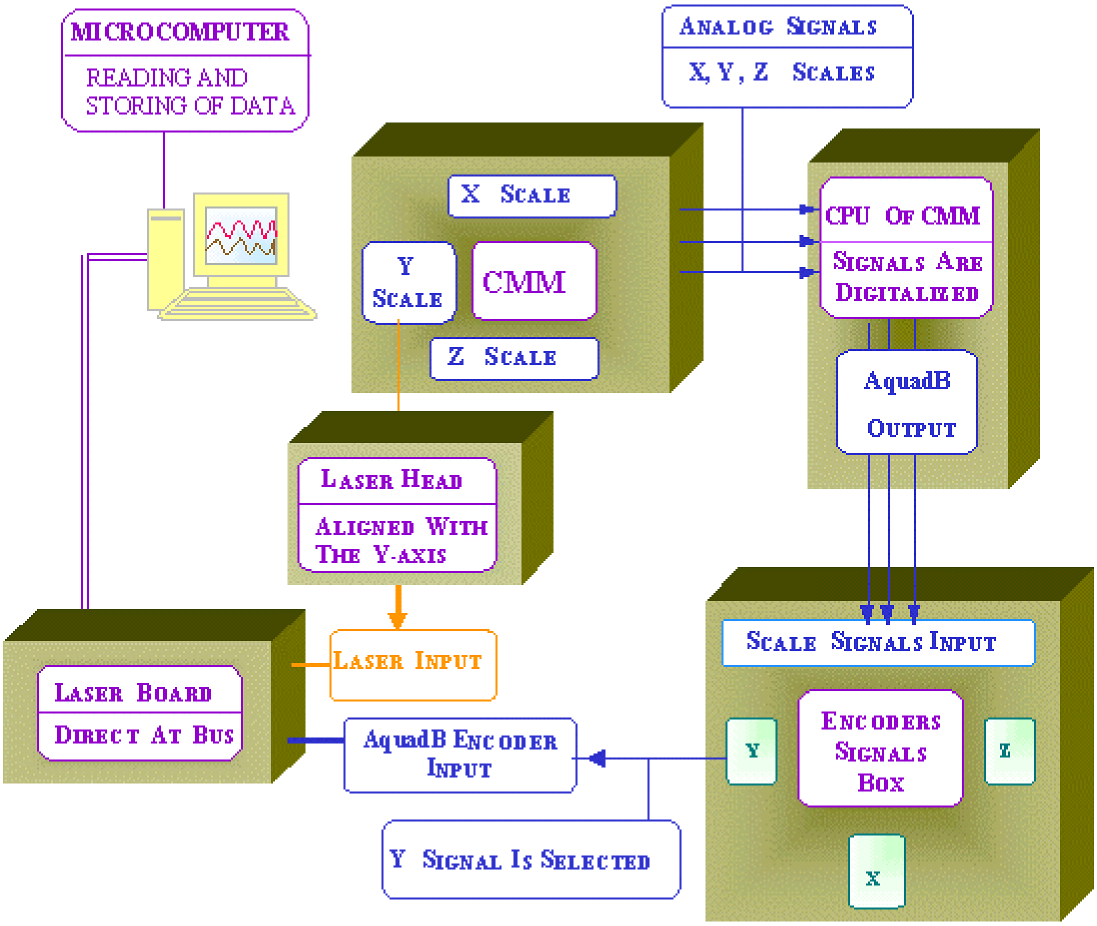

Figure 2. Schematic representation of system used in the data acquisition of low frequency cyclic error.

Fig. (2) shown a schematic representation of system used in the data acquisition of low frequency cyclic error. The analogic signals from the CMM X, Y, Z scales (sine waveform) enter in CPU of the machine where they are digitalized (square waveform) and put into an AquadB output. Soon afterwards, they enter in the encoders' signals box through the scale signal input. The interest scale signal, in this case Y, is selected electronically and it continues for the Aquad B output of the encoder. Through the HP 10887 PC Calibrator Board, connected to the microcomputer, this signal is introduced in the laser CPU. In this same board also enters the signal of the laser head. The function of this board is the triggering and "freezing" of the signals (AquadB and laser head) so that later the computer can read and to store the data.

The readings of machine and laser are compared and the HP 10747A software, installed in the microcomputer, presents the difference between them. The calibration data can be transfered for a file and analyzed through spreadsheets or text files.

3.2 Fast Fourier Transform Analysis (FFT)

A signal is a physical magnitude variable in time or space that contains some type of information, usually about the state or behavior of a physical system. In the case of a periodicity or cyclic pattern in the data, the signal can be completely described in the space domain. Many times it is convenient an analysis of the signal in the frequency domain. This occurs when a space function is composed of several frequency components. Whilst there is physical signal in the space domain one can say that in the frequency domain there are the signal components. The signals analysis in the frequency domain here is made through the Fourier Analysis.

The low frequency cyclic errors data was obtained during tests of 20mm length with incremental step of 0.024mm, in the initial part of the scale and with five unidirectional runs.

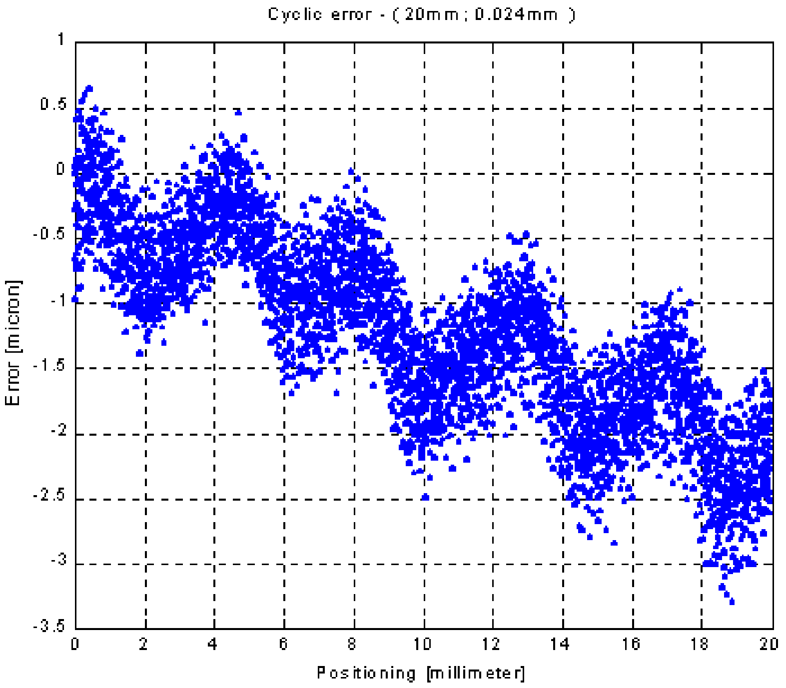

Figure 3. Cyclic error unidirectional test 20mm length and interval of 0.024mm.

The data files were presented in two columns regarding the position values, in millimeters, and positioning errors, in micrometers. The graph in the space domain, Fig. (3), presents error amplitude of approximately 2µm and cyclic period of approximately 4 mm. The presence of decreasing progressive error was also observed. To verify exactly which frequencies were present in the measured phenomenon it was applied the Fast Fourier Transform (FFT) to the values of the error. In the frequencies axis was used the unit cycles/meter. The F_i values of frequency axis was plotted using the following criterion:

$$F_i = i * (1/L);\ i = 1, 2, ..., N/2 \qquad (1)$$

where
N: total number of points
L: measured length

For the construction of the amplitude axis, the absolute value of each complex number produced by FFT was calculated. Afterwards the spectral graphic was plotted.

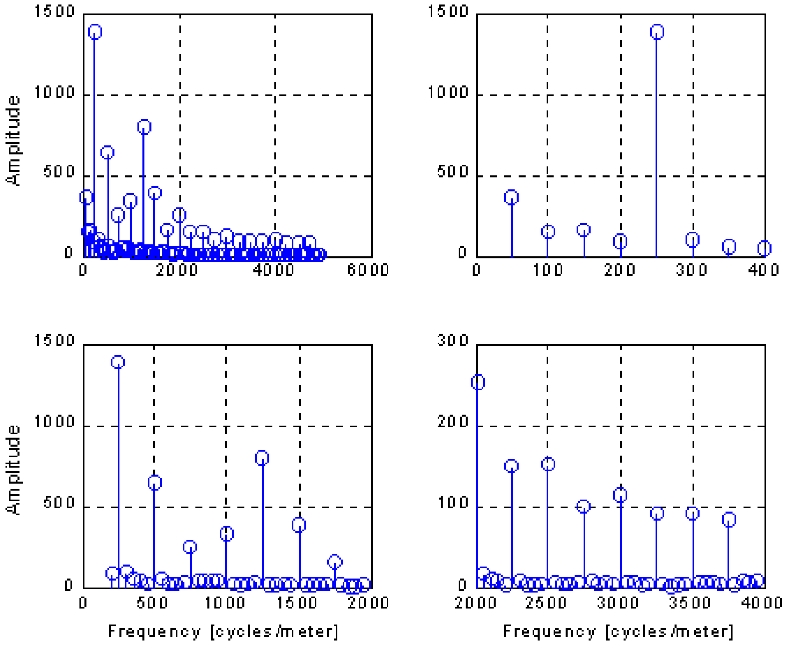

Figure 4. Frequency spectrum of cyclic error unidirectional test

The frequency spectrum presented in the Fig. (4) shows some of dominant frequencies, which are 250cycles/m, 500cycles/m, 1250cycles/m, 750cycles/m and 1500cycles/m. According with the Fig. (4), the most evident frequency present in the data is the one of 250cycles/m that corresponds to the cyclic period of 4mm. In relation to the other frequencies, specific tests should be made to verify if those frequencies represent real cyclic periods or aliasing.

Tests regarding the length of 20mm with incremental pitch of 0.064mm were made in five bidirectional runs, in the central part of the Y-axis scale. The same previously described procedure was applied to the data set. The error amplitude was of approximately 1.8μm and the cyclic period of approximately 4 mm, Fig. (5). The presence of small progressive error, in both travels, was also observed. Besides, it was verified hysteresis of approximately 4.5μm.

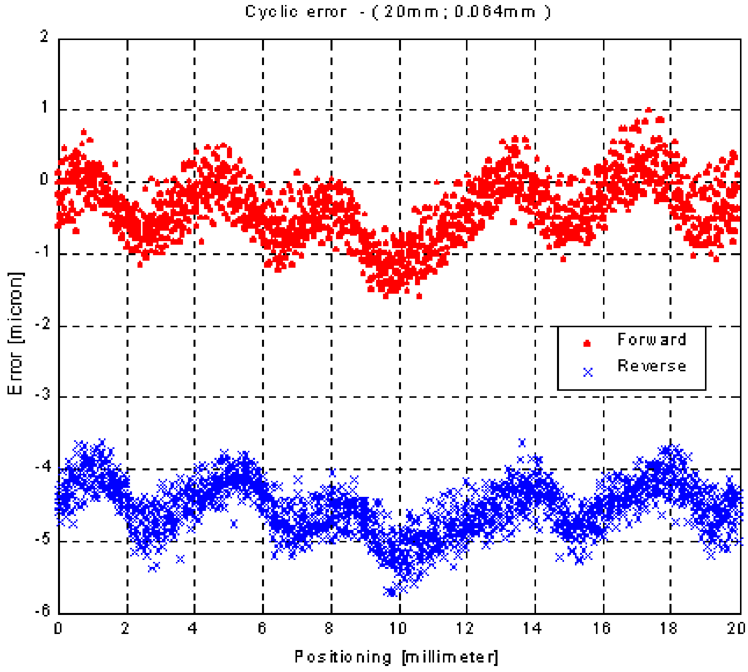

Figure 5. Cyclic error bidirectional test of 20mm length and interval of 0.064mm.

FFT was also applied to the data set.

By the graphic analysis of Fig. (6), it can be verified that the frequency of 250 cycles/m shows the larger amplitude in both travels, forward and reverse. Other suspicious frequencies, due to their great amplitudes, were 1250 cycles/m, 100 cycles/m, 500 cycles/m, 1500 cycles/m and 750 cycles/m.

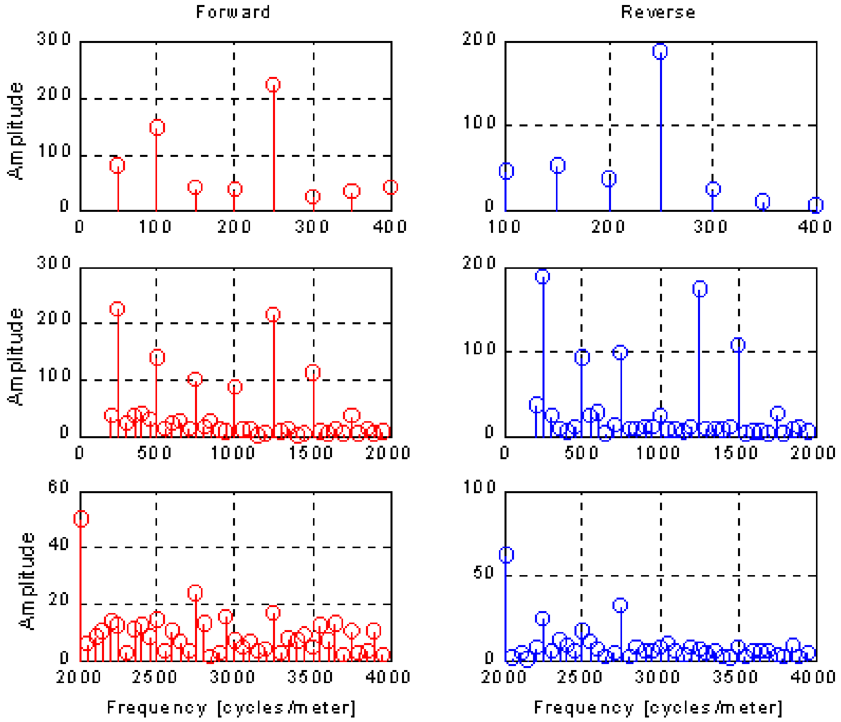

Figure 6. Frequency spectrum of cyclic error bidirectional test.

3.3 Conventional measurement of the spacing between scale lines

The displacement of one grating pitch moves the fringe vertically of fringe pitch. Pitch is the distance between a dark line and the end of the adjacent light line. Based on this fact, it was accomplished pitches measurement of approximately 10mm of a CMM’s moving scale. The measurements were made on a table of a digital microscope, with 25mm displacement in steps of 16µm and 400 times lenses. A photo of a measured scale shown in Fig. (7), suggests that during the compensation the dark lines become thicker and the light lines thinner.

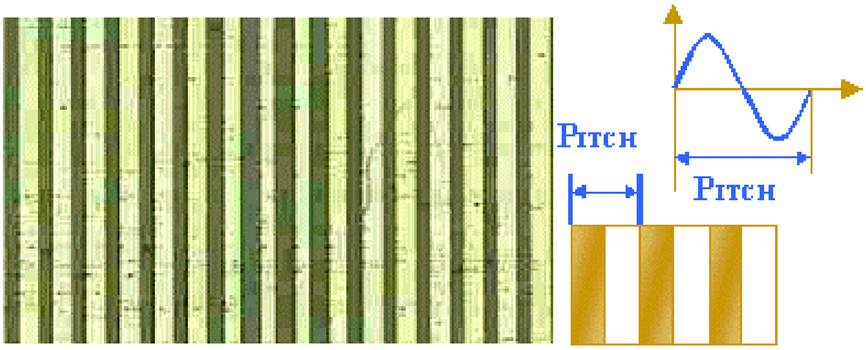

Figure 7. Photo of CMM moving scale and scheme of pitch measured.

The expected distance between consecutive lines of the scale, pitch, is approximately 16µm, however, measurements have shown different values, presented in Fig. (8) in a error graph form.

Through this graph, Fig. (8), was possible to verify that the compensation of the cyclic error, due to the scale lines manufacturing process, occurs at every approximately 4mm. The plotted graph also shows the presence of a progressive error originated by the compensation residues.

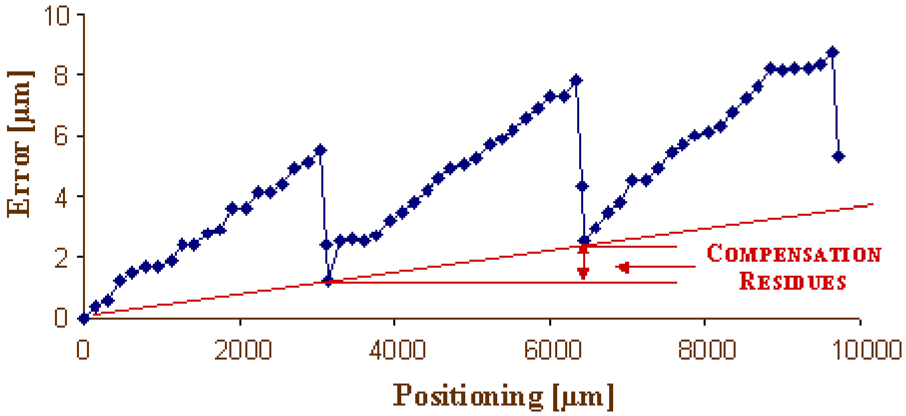

Figure 8. Resulting graph of the measurement of the spacing between scale lines.

3.4 Cyclic influence in the positioning error

During the calibration, usually, the positioning errors are collected at target points separated by 25mm one of the other. A strategy used to minimize the cyclic effect that can be used is the acquisition of data in the neighborhood of these points. To establish the size of this neighborhood width the period of the cyclic error should be taken into account. The positioning error value in a point will be determined, in this case, as being the arithmetic mean of the values collected in this point and in its neighborhood. The strategy works as a low pass filter.

Firstly, the positioning error of the Y-axis, for 20°C, was measured without taking into account the cyclic period. Afterwards, measurement was made using the strategy previously described. In Figure (9) it can be observed that the interval of standard deviation is much smaller, due to the adopted measurement strategy, and the effect was reduced in approximately 65%.

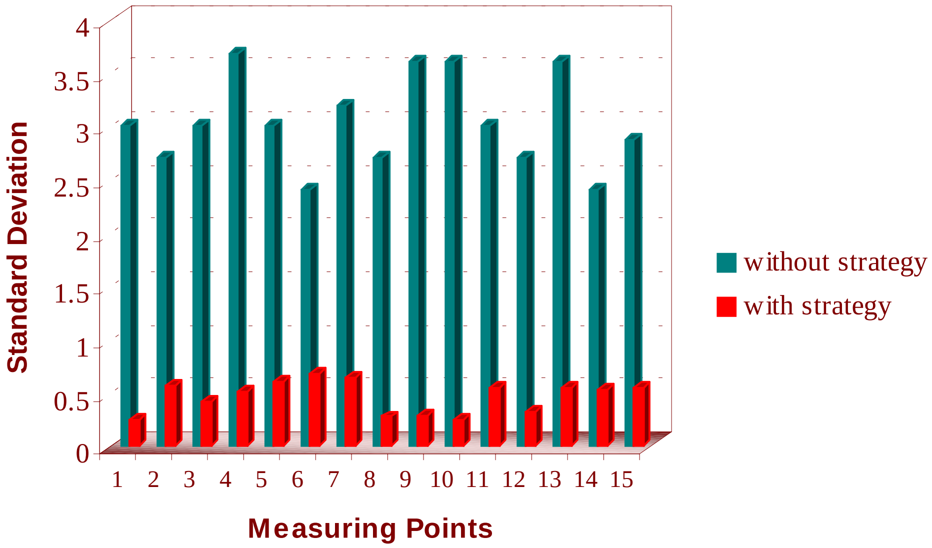

Figure 9. Standard deviation with and without strategy.

4. Conclusions

From this work, the following conclusions can be presented.

The cyclic errors can sometimes be imperceptible and, at other times evaluated with the wrong period. Measurements in 20 mm of the CMM Y-axis using an increment of 0.024mm made possible the visualization of a cyclic period of 4mm. The same result was also obtained during tests using 20mm of length with increment of 0.064mm.

The confirmation that other suspicious frequencies are really cyclic periods will be only possible with specific tests addressed to their data acquisitions.

It was verified that the compensation of the cyclic error, due to the manufacturing process of the scale lines, really happens, but does not exempt the machine of large systematic errors in the period.

The great advantage of the strategy to minimize the cyclic effect in the measurement of the positioning error is the decrease of the standard deviation of the results in approximately 65%.

Similar strategies can be applied during the workpieces measurement process minimizing therefore the presence of cyclic errors effect.

5. Acknowledgement

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