Tampereen teknillinen korkeakoulu
Julkaisuja 280

Tampere University of Technology
Publications 280

Jouni Hölsä

Method for Analysing Planar Machine Tool Measurements

Thesis for the degree of Doctor of Technology to be presented with due permission for public examination and criticism in Festia Small Auditorium 1, at Tampere University of Technology on the 10th of December 1999, at 12 o'clock noon.

Tampere 1999

HÖLSÄ, Jouni: Method for Analysing Planar Machine Tool Measurements

Department of Mechanical Engineering, Institute of Production Engineering,
Tampere University of Technology, Finland, 1999

Keywords: measurement analysis, machine tool testing, circular test, quality capability, machining centre

Abstract

This work presents a new analysis method for machine tool measurements. It is capable of analysing direct and indirect dynamic measurements in a plane. The analysis system is mainly intended to be used in flexible manufacturing systems with automatic measurement capability.

The analysis method is a further development of the analysis used in double ball bar (DBB) measurements. The new method includes also the handling of vectors and points in the measurement paths. This enables the use of the analysis system for a great variety of measurement methods as long as they are located in one plane only. The system can handle some servo and test piece related deviation types as well.

A study of different measurement methods that can be used with the analysis system is presented at the beginning of the theoretical part. 11 different methods available have been found, which demonstrates the available application potential. A sketch for the implementation of the automatic measurement system is given at the end of the paper.

The analysis system is practically tested with double ball bar, cross grid encoder and co-ordinate measuring machine measurements. All the measurement results are analysed with the new method and then the analysis results are compared with each other. The same machines are measured with direct methods and results are compared with the results achieved from the test pieces in a co-ordinate measuring machine.

The repeatability of analysis results of similar measurements is determined. Direct measurements, in general, show low enough repeatability values, but the test piece measurements do not necessarily fulfil requirements, set to machine tool measurements. The problem with the test pieces is that accurate enough co-ordinate measuring machines are not commonly available.

Expectable results are being found, showing that results of direct and indirect measurements are not always congruent. The correlation depends on every different case. Thus we come into the conclusion that an indirect measurement can be used instead of a direct measurement only, if correlation is verified earlier for the particular machine tool. The decision on the way measurements are completed, is important for economical repetitive condition monitoring.

One can come into the conclusion that the analysis system is usable for automatic follow-up of machine tools. The analysis is not, however, perfect and thus it requires calibration before the actual production run. The greatest advantage of the system is that it can incorporate many measurement methods into one general monitoring system that makes continuous follow-up of the condition of machine tools.

Foreword

This dissertation is the result of my work in the Institute of Production Engineering at Tampere University of Technology during the years 1995-1999. The first part of the work belongs to the FMS Maint System project (Eureka Maine) and the latter part of the work was financed by the Graduate School Concurrent Mechanical Engineering (GSCME, Academy of Finland).
I am very grateful to my supervisor professor Seppo Torvinen for his encouragement, support and arrangements. It is sure that without his pressure this study would not be ready yet.
I am also thankful for all the stuff of the institute. I have received invaluable practical assistance from Timo Antila, Olli Pirttiniemi, Matti Raiski and Matti Lehtonen. Additionally I have got very fruitful discussions concerning my work with Risto Pihlanen, Pasi Oksanen, Jorma Vihinen, Heikki Tikka and Paul Andersson. Altogether I have to say that I could never finish this work without their assistance.
Discussions together with professor Adolf Frank, doctor Karl Meitz, researcher Rahman Mahbubur and professor Yoshiaki Kakino have helped me to get a broader view to my research topic. The co-operation with them has offered me also possibilities to apply theories in practice.
Finally I would like to thank you for the background support that I have received from my parents and from Hélèna. They have given me the environment that has let me to dedicate in peace to my work.

Jouni Hölsä
Salomaantie 24-26 D15
33920 Pirkkala
Finland
email: jouni@pe.tut.fi

Tampere, November 1999.

Contents

Abbreviations

ANSI	American National Standards Institute
ASCII	American Standard Code for Information Interchange
ASME	American Society of Mechanical Engineers
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CCD	Charge-Coupled Device
CCW	Counter clockwise
CMM	Co-ordinate Measuring Machine
CW	Clockwise
D-H	Denavit-Hartenberg notation
DBB	Double Ball Bar
DIN	Deutsches Institut für Normung, Germany
DIS	Draft International Standard
DLL	Dynamic Link Library
DMIS	Dimensional Measuring Interface Standard
ETVE	Environmental Temperature Variation Error
FEA	Finite Element Analysis
FMS	Flexible Manufacturing System
ISO	International Organisation for Standardisation
LAN	Local Area Network
LBB	Laser Ball Bar
LSC	Least Squares Circle
LVDT	Linear Variable Differential Transformer
MZC	Minimum Zone Circle
NAS	National Aerospace Standard, USA
NC	Numerical Controller (equal to CNC, Computerised Numerical Controller)
NURBS	Non-Uniform Rational B Spline
PLC	Programmable Logic Controller
PTB	Physikalisch Technische Bundesanstalt, Germany
SFS	Finnish Standards Association
TUT	Tampere University of Technology, Finland

Symbols

α_t	Angle of line *t*
β_t	Approach angle of the point *t*
φ_i	Position along the line
θ_i	Angle at a measurement point *i*
A	Prototype matrix
$\underline{d}$	Estimate vector of deviation type magnitudes
dir_t	Direction of rotation {1 if counter-clockwise | -1 if clockwise}
f_t	Feedrate on the feature *t*
i	Measurement point number
l_x	The half of the total width of the measurement along *x*-axis
$\underline{m}$	Measurement data vector
$\underline{p}_{deviation\_type}$	Prototype vector of *deviation type*
R_t	Radius of the circle *t*
s	Standard deviation
t	Feature number
V	Covariance matrix
x_0	Centre point of the measurement, the 1st coordinate
$x_{0,t}$	Centre point of the circle *t* or position of the point *t*, the 1st coordinate
x_i	The 1st coordinate in position *i*
y_0	Centre point of the measurement, the 2nd coordinate
$y_{0,t}$	Centre point of the circle *t* or position of the point *t*, the 2nd coordinate
y_i	The 2nd coordinate in position *i*

1 INTRODUCTION

1.1 General

The approach of this work is to represent a new method for analysing machine tool measurements. Figure 1 shows a block “External geometry inspection”, which is the area this paper concentrates on. The results of the work are disclosed by two ways, both as a software program and in written form in this thesis.
Here, some measurement methods and general accuracy issues are presented in a level that is seen to be relevant to the whole work. Also the motivation for the work is being stated. Objectives of the paper and restrictions are described in chapters 1.5 and 1.6.
The reader must know that a great effort is put world-wide on improvement of accuracy of machine tools. Mechanical, electrical and software solutions are being developed to achieve higher accuracy. A question arises: “Why all this effort?” This paper is not going to give an answer to this question, but it tries to promote development in this field by offering a new economical and robust analysis method.

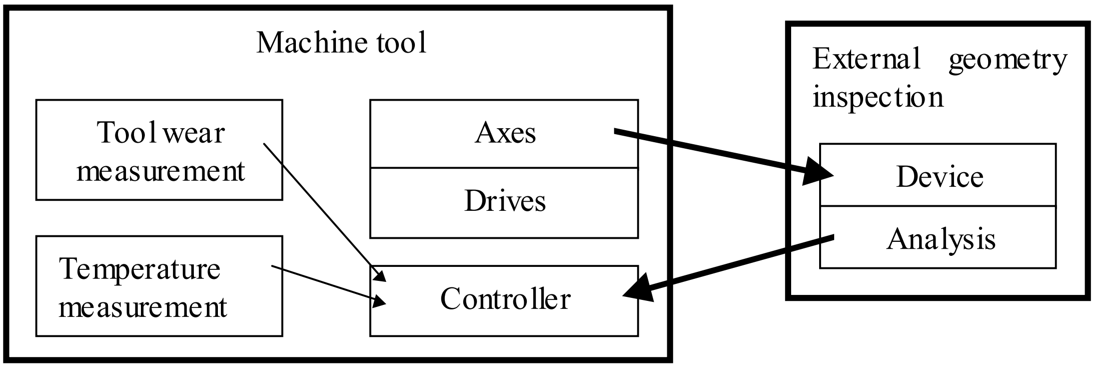


Figure 1. Quality feedback loops in a machine tool

1.2 Needs

Manufacturing systems are not modernised nor enhanced, if there are no economical benefits to achieve. Modern measuring, analysis and compensation systems for machine tools can offer a couple of enhancements that will lead either to bigger income or smaller costs. These effects can be seen at a company level and at a level of the whole society.

1.2.1 System automation

If a specialist carries out machine tool measurements, advantages gained with an analysis tool, are not crucial. A specialist can in most cases tune a machine tool by rote looking at the measurement result graphs. It is good to notice that not all specialists interpret results the same way and thus methodicalness is missing.

However, if machine tool measurements can be automated [chapter 5.6.4], an analysis tool becomes essential. The whole follow-up chain can now work autonomously, both monitoring and tuning the production system [chapter 2.3.3]. Without an analysis tool the specialist should analyse each measurement manually and then store the results. The work is extensively monotonous, and the risk for human errors is great. Also the repeatability of results suffers from unavoidable inaccuracies of human interpretation. Automation is a tool, used to achieve higher goals in production systems, just like productivity, usability etc. From the point of view of analysing the machine tool measurements, automation itself is a goal. The general advantages, claimed later in this chapter, can be achieved by means of automation.

1.2.2 Costs of design

Manufacturing facilities can give feedback to the product design department. This gives to the design better knowledge on possibilities and equivalent costs of the production. With a frequent measuring this information can be up-to-date and reliable. When this information is available in an early stage of design, it is possible to select the right kind of a manufacturing method and a routing for gaining both an economical and fluent manufacturing process.

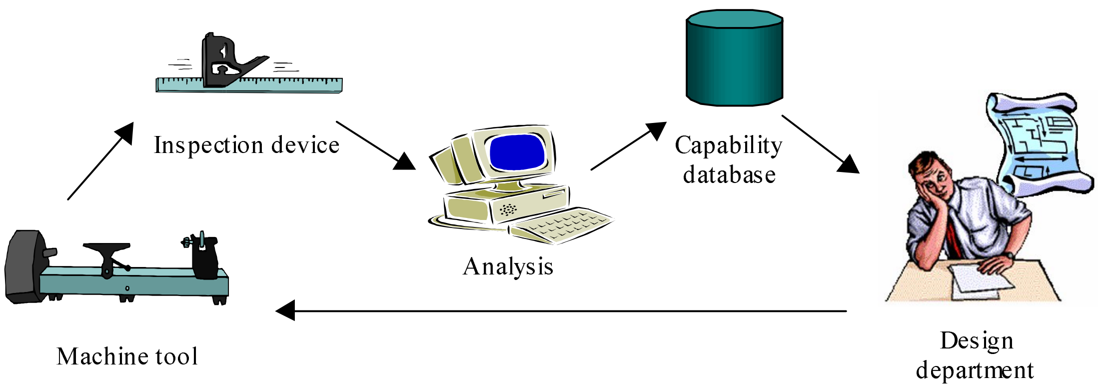


Figure 2. Capability information flow to the design

The feedback to the design requires a measuring system, analysis and network database that can be utilised by design tools. The measurement information has to be shown to the designers in terms of the capability of a manufacturing process to produce quality for specific features [Donmez 1996]. In other words a designer has to be able to draw parts using the features in CAD (computer aided design) and, at the same time, to know how accurately those features can be manufactured and at what cost.

1.2.3 Ecological aspects

Higher production accuracy, better surface quality and right fittings give a longer life to a product and also lower the consumption of energy. Frequent machine tool measurements and compensations help to achieve all these goals. Short compensation intervals keep deviation range low and known in advance so that the functionality of devices, produced by those machines, is what the designer had originally planned. Ability to produce parts of higher accuracy gives better efficiency in general.

Because the manufacturing process is better under control, there are less defective parts as well as less waste and less useless power-up time of machines. This enhances ecological side of the production itself.

1.2.4 General product quality needs

Many new products have now been designed more accurately than before and thus also require a more exact manufacturing process. Frequent measurements of manufacturing tools can guarantee the capability of the manufacturing process. When measuring is combined with compensation of machine tools, one can also achieve a higher end quality of the products.

Therefore, compensation and measuring have two benefits: they assure that the range of variation is small and put the average level of variation lower. This makes the manufactured products to fit with in a given specification.

Higher manufacturing accuracy makes it possible to design products of higher quality demands. This again can offer both better functions and higher performance of the end products.

1.2.5 Availability of machining capacity

We can have three scenarios, the first one is to use machine tools without any or with few inspections, inspect machines often with conventional methods or inspect machines often with an automatic system.

When no inspections are done, there exist a greater possibility of sudden breakdowns, faulty products, and unsatisfactory quality. Those will occur without any warning and then require fast actions, but unfortunately, it is not always possible to get service staff as fast as it would be desired. This will lead to increased machine downtime. Frequent inspections with conventional inspection equipment guarantee high product quality, but it is expensive in terms of service personnel time and downtime of machine tools.

Automatic inspection procedure can perform checks when it is more convenient, for example the small hours of every fifth day. The inspection times can be scheduled according to the production queue, and the inspection time itself is shorter than of a conventional inspection. But again, frequent tests guarantee quality capability of machine tools.

1.2.6 Quality systems

Quality systems require that at least the actions of the production department are documented. Also the history of a single product must be traceable in some fields like aviation industry. The follow-up of machine tools is not usually directly required in a quality system. But from the point of view of the product quality and the general level of activities, regular follow-up of machine tools fits very well in quality systems and it supports other actions, that exist there already now. Indeed, ISO9001 requires that "monitoring and control of suitable process parameters and product characteristics" shall be controlled [SFS-EN ISO 9001: 4.9.d].

When a follow-up of machine tools is determined to be a part of a quality system, an automatic inspection and analysis system can fulfil those requirements. Follow-up and traceability are important for a quality system. The quality system requires that each measurement and compensation action must be recorded in a database [SFS-EN ISO 9001: 4.16 and 4.20.2]. This offers information for other systems and acts at the same time as a reporter of the quality system.

1.3 Accuracy of machine tools

The accuracy of a machine tool is based on its foundation, frame, slides, driving system and controller. Each component cause its own kind of deviations in the realised motion of a machine. Measurement of accuracy is significant to machine tool builders and their end-users, because the accuracy of machine tools is to be seen directly in the quality of the parts manufactured with those machines. One important issue in the accuracy of machine tools is thermal behaviour, because it causes some changes in all mechanical components.

Machine builders and controller industry make continuous work to improve components in order to make new machines more accurate and affordable to manufacture. Interests of machine tool builders and end-users differ from each other. The scope of development in machine tool building is to make new machines better in their performance and accuracy. The durability of those characteristics is not in the direct interest of a machine tool builder. End-users instead, are interested not only in accuracy of new machines but also to know their current state. Information shall be used to file the condition of machines and to adjust them.

Inaccuracies arise mainly from mechanical parts of machines. These deviations can however be compensated in some amount by a controller. Development of numerical controllers has offered flexible compensation methods for machine tool builders and end-users. Only machine builders have so far had means and knowledge to exploit this new feature, but for end-users attaining measuring information has been too complicated a task. However, these compensations do not offer a mean to enhance accuracy of a new machine only, but also a better tool they are for maintaining the good accuracy of machines. Thorough research has been carried out to study the possibilities to both compensate machine tools and co-ordinate measuring machines [Schellekens et al. 1998].

1.4 Machine tool measurements

Machine tool measurements are carried out in order to examine accuracy of the motions of a machine tool. Here it means to measure the motion of a tool in relation to the one of a table. Thus it involves slides, a driving system and controller effects. Typically the examination of accuracy is performed for a new machine during installation, in the acceptance of the delivery, after collisions, and after major services.

However, in some cases these measurements are performed regularly to ensure quality of production and to fulfil requirements of the quality system. This practise has spread out from aviation industry, where it was first used to follow the strict requirements of the safety regulations.

Roughly, machine tool measurements can be divided into two categories. The first one of those is static measurements, and the second one the dynamical ones. The history of measurements starts from the static measurement as all the lately introduced methods are dynamical. Some fixed points, where machine stops are measured by

static measurements and continuous positioning data, are collected by dynamical measurement.
Numerous other classifications also exist. For this study it is relevant to divide the subject into direct and indirect measurements. Direct measurement measures actual positioning of a tool, as a manufactured piece in a machine is measured in the indirect measurement. However, both types can be either static or dynamical. Indirect measurement involves more error sources than direct measurement, i.e. cutting and fixing forces and errors of a measuring machine. Usually a co-ordinate measuring machine (CMM) is used to measure those pieces and it is typically one or two degrees less accurate than the direct measurement devices. However, indirect measurement reveals important information on real accuracy of process especially when material and tooling, equivalent to those in real production, are used.

1.5 Hypothesis and objectives

The research presents a new system to analyse machine tool measurements. The method is fast, easy to use, reliable, and applicable to a number of measurement methods. Furthermore it supports dynamic measurements contrary to most existing methods known this far.
Measurement methods developed during the last decade, have created significant new possibilities for measurement of accuracy of machine tools. This potential should be exploited to improve the quality of manufacturing. This means that the measurement information is used to file quality capability level of manufacturing tools, to follow the condition of machine tools, and to adjust them when feasible.
The analysis and follow-up method described in this paper utilises a wide range of currently available measurement methods. All the results are gathered under one system, that can file the quality capability, follow-up machine tools, and give the tuning information. It is proved that this system gives results equivalent to already established methods and the inner uncertainty of the system is determined by experiments.
Advanced analysis theories have been developed to analyse machine tool error origins based on measurement sets. These methods work well when measurements are carried out in a way the analysis method requires. However, this causes in most cases the measurements to be laborious and time-consuming. The method presented here is easy to use and applicable without modifications in machine shops.
The work goes forward in phases, which are based on the work of an earlier phase. Empirical part of the work gives feedback to first phases and thus altogether the process is iterative. Concrete objectives of the thesis work are the following:

1. *Create theory for analysis*
2. *Develop software based on the theory*
3. *Show that the analysis system gives consistent results for different direct measurement methods*
4. *Show that direct free form measurements can be used instead of test pieces*

1.6 Research approach

This research has been carried out, using three different research approaches to verify the proposed method. First, a simulation model have been used to verify the presented model, secondly, controlled experiments are run in a laboratory, and thirdly, a field study has been made to survey the generality of the proposed system. [Classification based on Järvinen and Järvinen 1993]
The approaches support each other and push the research forward. Even of principally the proposed method would behave just perfectly can experiments in controlled environment bring up some new aspects. Still, after controlled tests, field studies may reveal phenomena not anticipated at the beginning of the study. Field studies can also show how well the system can be generalised to different environments and how sensitive it is to common disturbances.

1.7 Scope of work

The work focuses on three-axis milling machines. The results are, however, applicable for a greater variety of machines having at least two linear axes. Rotational axes are not considered in this work.
The presented analysis method handles geometrical and some servo tuning related errors. It doesn't deal with thermal behaviour and compensation. Thermal and tool wear compensations are considered to be a separate task that have a higher update frequency and a closer integration with a machine tool [Figure 1]. Thus it is not preferable to involve these deviation sources with geometrical errors.
The analysis method handles all the measurements in a plane. It does not analyse three-dimensional errors though that kind of an analysis can achieve higher accuracy and exactness. However, planar analysis can offer good generality, ease of use, good variety of available standard measurement devices and fast computation.

2 AVAILABLE TOOLS

2.1 Quick measurement methods

The measurement methods introduced here are applicable together with the analysis method presented later. They all also offer some potential to be used automatically without human intervention even if this functionality hasn't been proved and tested this far. Double ball bar, cross-grid encoder and co-ordinate measuring machine have been used in the practical part of this work.

2.1.1 Double ball bar

Double ball bar (DBB) was developed in the early 80's and it has become increasingly common during the 90's. DBB is based on a very accurate linear scale, which measures changes in radial direction during a circular motion.

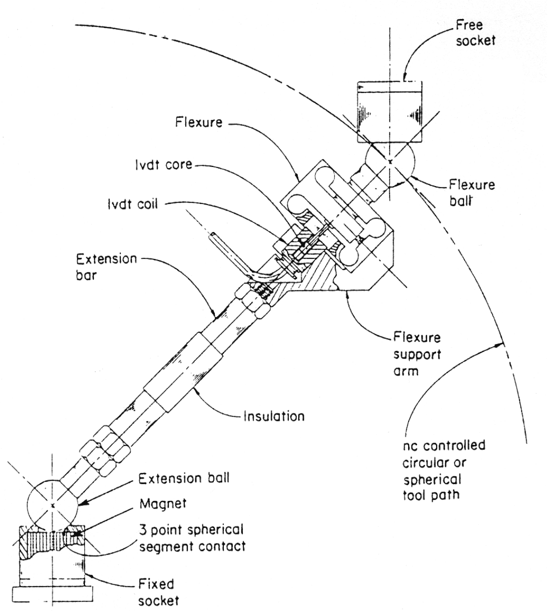


Figure 3. Double ball bar [Bryan 1982]

The most important limitation of this device is that it is only capable of measuring points in circular trace. The measurement type itself can be either a circular test or a static measurement. A circular test is a dynamic measurement with a constant feedrate. A static measurement instead involves some positionings in a circular trace. The both test types are very fast to accomplish and the device itself is rather cheap. The evaluation of results is well studied and many of the most significant formulae can be found in literature [Kakino et al. 1993]. Standardisation organisations have also published some standards concerning double ball bar measurements. The most important of those are ISO230-4 and ANSI B5.54-1992. This ensures unified practices in ball bar measurements and makes it possible to reliably find many machine tool deviation types out of this simple measurement.

It is preferable to measure a whole circle with this device. That way it gives more accurate and reliable results. It is possible to measure only partial circles though and sometimes it is more convenient from the point of view of the measurement set-up. This concerns most of all lathes, though with some special equipment it is possible to measure the whole circles in lathes too, which is therefore recommended. Semicircle measurement has some limitations, concerning both deviations which can be found, and the accuracy of analysis.
The comparison between DBB and laser interferometer has been studied in practise [Oksanen 1997]. The research has shown that double ball bar reliably reveals most deviations. However, it cannot find reliable values for straightness or angular deviations.

2.1.2 Cross-grid encoder

The cross-grid encoder is a relatively new device, making it possible to perform all kinds of free form tests in a plane, including circular tests. The device belongs to the category of quick test devices, but it has also versatile capabilities to assist in servo adjustments.
This device is based on the working principles of optical scales. There are two light sensitive sensors and light sources with a lens system in the read head, one for both measurement directions. The read head scans over a cross-grid plate, which has a waffle like pattern engraved on it. The grooves reflect the light back to optical sensors, causing a sine wave formed electrical signal. This signal is counted on a special counter card attached in a computer.
The accuracy of the device depends heavily on the accuracy of the plate. Whereas the measurement feedrate depends on the bandwidth of the counter electronics and the distance between two engraved lines on the plate. Nowadays it is possible to achieve an accuracy of ±2µm and a feedrate around 24 m/min with this device [Heidenhain 1998].

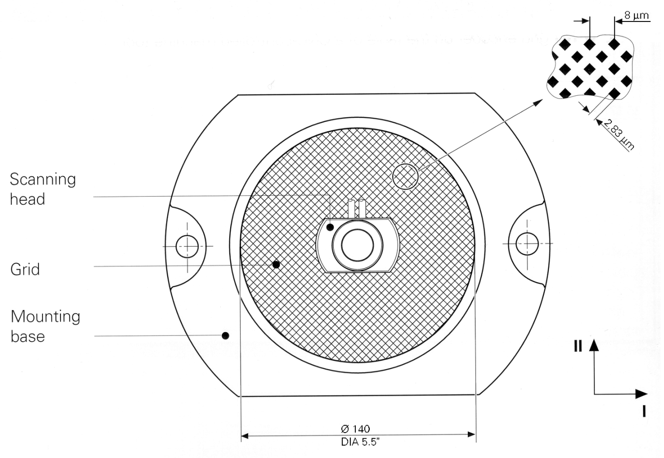


Figure 4. Cross-grid encoder [Heidenhain 1998]

One of the disadvantages of this device is the accurate measurement arrangement it needs and its limited measuring range (currently ∅230mm on KGM182 [Heidenhain 1998]). A comparator system is also available using the same technique. It has a long

measurement length and a short measurement range in cross direction, too (currently 1520mm in length and 2mm in width with VM182 [Heidenhain 1998]).
The measurement plate has to be aligned with machine tool axes. This should be done with an accuracy of 0,2 degrees to guarantee that the measurement can be completed without loosing the effective measurement signal. The alignment error of 0,2 degrees causes also 0,8µm scaling error and half a millimetre deviation perpendicular to the plate. This error can be observed in measurement results, but as it comes to machine tools it is of little consequence.

2.1.3 Co-ordinate measuring machine

Both test pieces and ordinary work pieces can be measured with a co-ordinate measuring machine (CMM) in order to evaluate the accuracy of a machine tool. A CMM measurement is not a real quick test method, but if those measurements would be accomplished anyway to guarantee the achievement of tolerance goals, a proper analysis could at the same time utilise those results more efficiently to reveal deviations of a machine tool.

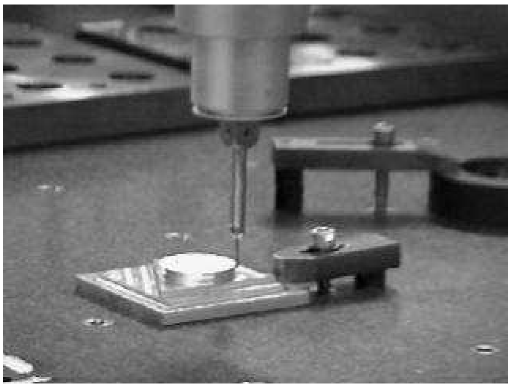


Figure 5. CMM measurement

CMM is not so accurate a piece of equipment like other quick check measurement methods. This has to be considered when evaluating a measurement. Deviations in a CMM itself cause similar kind of deviations to be found in an analysis. These deviations should be distinguished from the similar kind of deviations of a machine tool.
The simplest way to handle this problem is to use a CMM which is one order more accurate than the machine tool to be inspected. This is not, however, realistic in most cases. This is because CMM's are not commonly so accurate as it would be needed for the analysis of machine tools. And when an accurate enough CMM is available, one should remember that the deviations found out by an analysis based on CMM measurements are partly caused by the CMM itself. When the uncertainty of a CMM is known, the uncertainty has to be added to the uncertainty estimate of deviation results achieved from the measurement.
If a production CMM used in measurements doesn't in all respects fulfil the needs of accuracy inspection of machine tools, it is possible to use the substitution method [ISO TC3/WG10]. We have to have a stable known test piece, which is measured with a CMM, having a high grade of accuracy. Now this same test piece should be measured with a production CMM. The measurement results are compared with each other and differences between the points of a high grade measurement and a

production measurement are calculated. The measurement should be repeated in order to find out the stability of a production machine. If stability is good enough, i.e. one decimal less than expected accuracy of the machine tools to be inspected, the method can be used. The deviation between measurement sets will be used to compensate all the subsequent measurement results of the test pieces of a production CMM. The test piece used for comparison and the actual test piece for production have to be equal or very close to equal. All the measurement paths, movement directions and probing forces etc. have to be equal, too.

2.1.3.1 Test pieces

A variety of different test pieces has been used to evaluate the accuracy of machine tools. There are several national (ANSI/ASME B5.54, DIN8606, NAS 979, VDI/VDQ-3444) and international (ISO 1984, 3070, 10791) standards on how a test piece should be machined available and many companies have also their own recommendations. The great variety of pieces has been caused by different kinds of needs and measurement possibilities available.

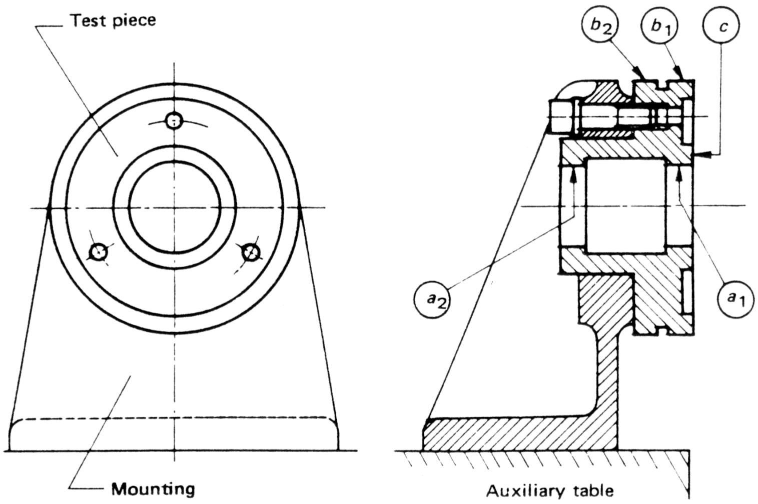


Figure 6. ISO3070/II test piece [ISO 3070/II]

The ISO 3070 test piece above can reveal values for circularity, cylindricity, concentricity, coaxiality, flatness and perpendicularity. Perpendicularity of those types only is a real direct error of a machine tool. Other deviations are more or less consequences of other unknown errors of a machine tool. Thus the standard itself does not tell in detail how to analyse the measurement data. It merely presents a method for manufacturing the piece, leaving conclusions to the measurer.

A specially designed test piece at Tampere University of Technology has been used in some research [Andersson 1992][Oksanen 1996]. This test piece is designed to reveal positioning error, squareness and backlash in two axes at a time (usually in xy-plane). The evaluation of the test piece is a straightforward process with the aid of a co-ordinate measuring machine.

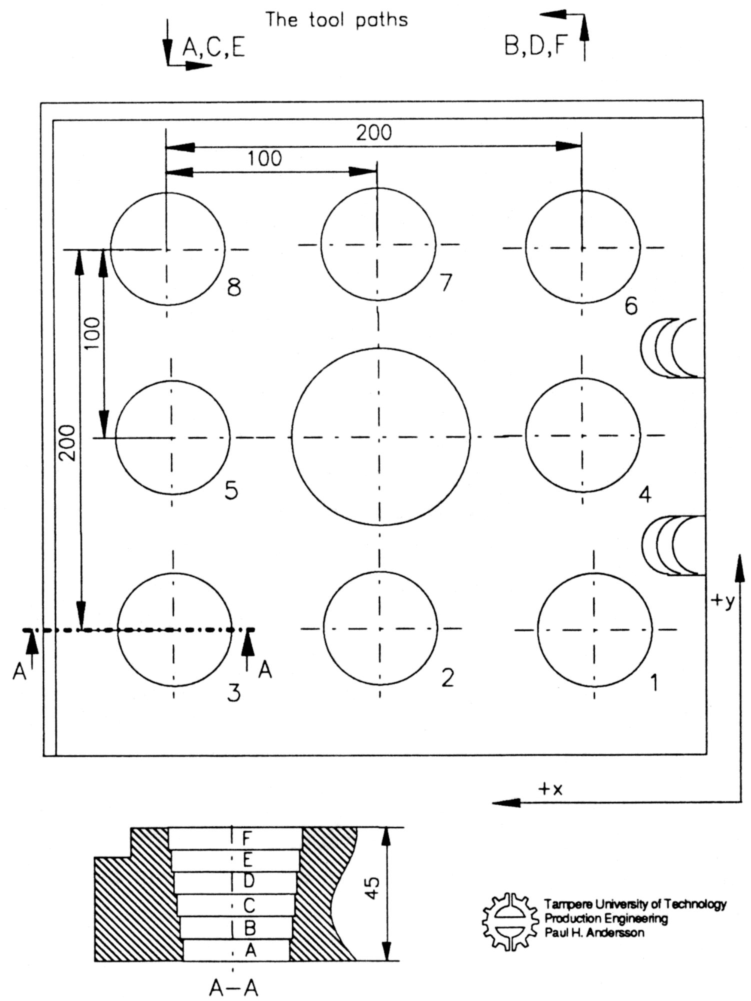


Figure 7. TUT test piece [Andersson 1992]

Multiple different test pieces can be used in order to reveal the wanted collection of deviation of a machine tool. For instance, three different kinds of test pieces were used in a research project to adaptively correct errors of a turning centre [Mou et al. 1995]. Each test piece revealed some deviation types and thus the information, observed from individual test pieces, supported each other. Features in the pieces were chosen in the way that they detect unambiguously certain deviation types. Information, got out of the machined test pieces, together with temperature information, were used to compensate a turning centre.

2.1.3.2 Workpieces

As the specially designed test pieces can include only suitable features to detect deviations of a machine tool, this is not necessarily the case in workpieces. However, it is possible that also those pieces include features that reveal some deviations of a machine tool. It is common that a machine tool can be partly analysed by using information from a workpiece only. It requires that the finishing part of a manufacturing process is well known, i.e. direction of machining, direction of approach, tool, orientation and position in a machine.

Attention in the analysis of workpiece measurements should be focused on the incompleteness of the results. They reveal only a part of deviations of a machine tool

and thus merely detect problems of a machine generally more than show exact values for some certain deviations. Another matter is that also the analysis method has to cope with this incomplete information.
Machining conditions may change considerably between measurements, when ordinary production pieces are used for a quality follow-up. The information on changes in the NC-program, cooling and tooling should absolutely go up to the analysis phase. Without proper background information crucial misinterpretations can easily occur.

2.1.4 Uni-Test

The Uni-Test equipment was developed to measure both machine tools and robots [Haas 1996]. This device can measure all the six degrees of freedom, which makes it possible to make a complete analysis of a machine. It also allows the user to make multiple tests on one setting. The disadvantage is that because of many joints, needed to measure all the degrees, this device is not as accurate as the competing methods.

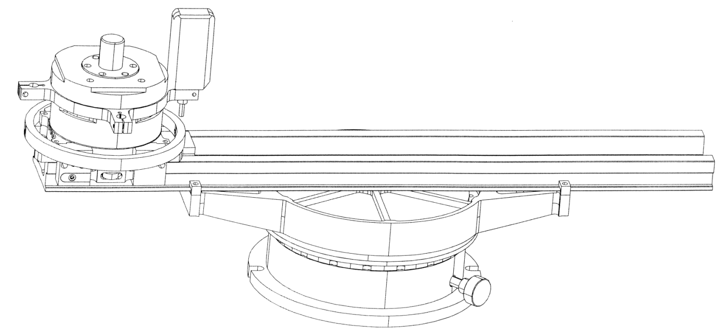


Figure 8. Uni-Test II [Meitz 1999]

The first version of the Uni-Test is equipped with an air bearing and this limits orientation of the device. It can be used only in a horizontal plane. The next generation of Uni-Test uses instead a high precision mechanical bearing, which allows free measuring angles [Meitz 1999].
The device consists of many mechanical and measuring parts, which cause errors in measurement results. However, these errors can mostly be compensated if an accurate enough calibration method is available. The compensation can be carried out for each axis individually by means of a measurement software. Each axis is measured and compensation tables for both movement directions are composed. Some errors will still remain because of the differences in measurement force, temperature variation and other changes in environment. It is possible to make this device accurate enough for machine tool inspections by the means of thoroughly good mechanical design and software. Preliminary practical tests have shown good results for this device.

2.1.5 Laser tracking

3D laser tracking devices are versatile pieces of measuring equipment, but in general they are not yet accurate enough for measurements of milling machines etc. This problem concerns especially the angular encoder needed in the device, whereas the laser interferometer part is similar to an ordinary laser measurement device and thus accurate enough. A standard laser tracker measures three position co-ordinates of a target retroreflector. Manufacturers offer two models, one with a less accurate absolute distance measurement and an other one with differential distance measurement. Positional measurement accuracy of a laser tracker is better than 50 µm/m and repeatability is below 10µm/m [Prenninger et al. 1995].

Nowadays a laser tracker can offer accuracy which is very well capable for inspecting robots. Some studies have been carried out to measure even orientation angles with a single beam laser tracker. The method is based on a retroreflector, having wires fitted in. Those wires create shadows in a detection CCD and the information can be used to determine an orientation angle of the retroreflector. [Prenninger et al. 1995]

2.1.6 Multifunction laser-interferometer

With a single laser-interferometer device it is possible to measure positioning, pitch or yaw of an axis each at a time. Development work has been done lately to combine those measurements in a single run. This has been realised by combining three retroreflectors and corresponding laser light sources together. Thus it is possible to capture all those measurements in one run using old tested measuring principles. A device has been developed, using this principle and diode lasers to study the behaviour of the system. Positioning measurement results have been good but no good results have yet been achieved for angular errors with this method. [Abou-Zeid et al. 1996].

The same measurement can be realised also by using Doppler lasers. The measurement is not as accurate as with a laser-interferometer, but the measurement installation is some what easier.

2.1.7 Autocollimator laser

Principles of an autocollimator can be used to measure many deviation angles of a machine tool at the same time. Further on this can be combined with straightness measurement. The method relies on two-dimensional photodetectors, which detect deviation of light reflected back from the measuring head. The helium-neon laser or a collimated visible laser diode can be used as a light source. With this method it is possible to measure lateral straightness, vertical straightness, pitch, yaw and roll errors.

The accuracy of the autocollimator laser depends greatly on the accuracy of photodetectors and beam pointing stability of the laser. Roll measurement is especially sensitive to all error sources and thus its reliability is rather low. [Ni and Wu 1993]

2.1.8 Laser ball bar

Laser ball bar (LBB) is a kind of a further development of DBB. Originally the method was developed to measure co-ordinate measuring machines, but it is applicable for machine tools as well [Tikka 1992].
LBB consists of a two-stage telescoping tube with a precision sphere mounted at each end. A heterodyne displacement measuring interferometer is aligned inside the telescoping tube and measures the relative displacement between two spheres. Because of the laser interferometer measuring principle instead of the LVDT, measuring range can be given in 100 millimetres compared to millimetres in DBB. The accuracy of measurement is also very good. Determinant error sources are balls, ball sockets and uncertainties in environmental compensations of laser.

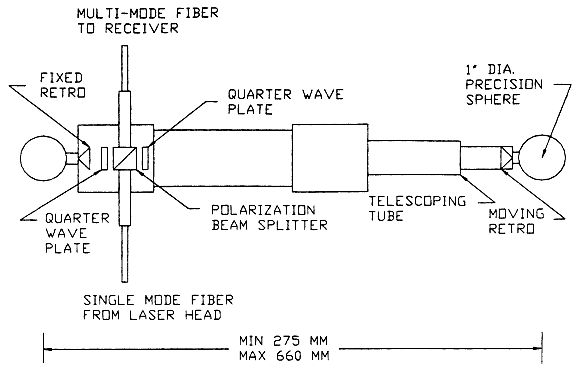


Figure 9. Laser ball bar [Schmitz and Ziegert 1998]

Because of the wide working range of LBB, it is possible to use them in a trilateration arrangement. This makes it possible to measure three dimensions simultaneously. The difficulty in the arrangement is to construct a three-point contact of all three bars to a single ball attached in a moving part of a machine tool (spindle or turret). Similarly, it is possible to use just two laser ball bars and measure with triangulation in a plane [Tikka 1992]

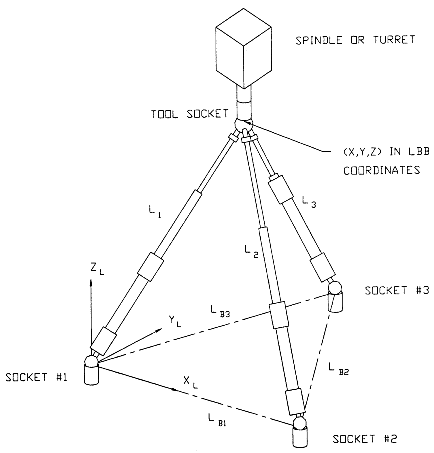


Figure 10. Trilateration with three LBBs [Schmitz and Ziegert 1998]

The method offers precise accuracy measurement with high sampling rate. Today Tetra Precision Inc. offers commercially a laser ball bar called OmniGage™, but the device itself and the methodology involved in the measurement are still under development [Krulewich 1998][Schmitz and Ziegert 1998].

2.1.9 Laser circular test

A method has been developed to use an ordinary doppler laser [Liotto and Wang 1997] to perform a circular test [Wang and Griffin 1999]. There are some dissimilarities to other circular tests in the testing procedure as well as in the measuring principles. The system is based on a flat mirror on a machine tool spindle and on two test runs that are performed in right angle to each other. Thus crucial factors for the accuracy are thus the flatness of the mirror and the perpendicularity of the turn of the mirror. Also the synchronisation of the two runs have to be performed well. This can be done either by giving a signal from the controller via PLC (programmable logic controller), or the measurement device itself can detect the start of the measurement autonomously. In order to detect the signal autonomously the performed runs must be placed in a 45 degree angle to the machine co-ordinate system.
The benefit of the device is that multiple other tests can be performed with the same equipment as well. It is possible to measure positioning, pitch, yaw and even squareness with suitable options. The measurement device itself (doppler laser) is an accurate device, however measurement installation inevitably causes some deviations in this measurement method. The system with different kinds of options is obtainable at Optodyne Inc.

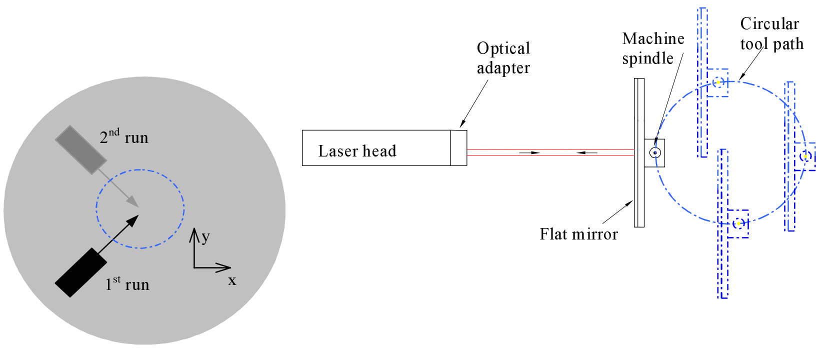


Figure 11. Laser circular test

2.1.10 Circular test with a scanning probe

One of the earliest quick test methods has been so called Knapp's test. A circular test method based on an accurate master ring and scanning measuring head was introduced in the mid 1980's [Knapp and Hrovat 1987]. This device is capable of performing a circular test, but it suffers from noise and friction. Only a fixed diameter test can be accomplished by this device.
A lot of valuable work was done to improve analysis of these measurements. This theory is still valid for other quick test measurements. Originally the test run was designed to be accomplished without a computer, and an analogue plotter was used to record the measurement data. Likewise analysis of results was to be performed by an operator.

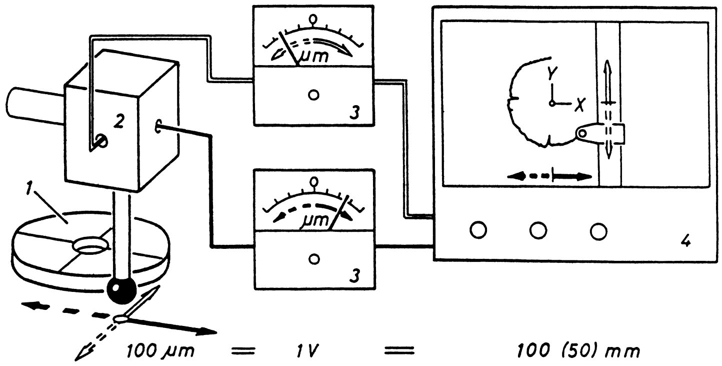


Figure 12. Circular test with a scanning probe [Knapp and Hrovat 1987]

2.1.11 Touch probe and an artefact

A touch probe can be used to make a quick test, when probe is used to measure a known artefact. This measurement data can be used like a CMM measurement, but the artefact must be specially designed for this purpose. Analysis and data capture must be integrated in a numerical controller to make this measurement method feasible. This kind of a system could fit well in flexible manufacturing systems, but special attention must be focused on questions concerning cleanliness of the artefact and the touching probe.

Ferreira and Liu [Ferreira and Liu 1993] have used a metrology pallet with two different length touch-trigger probes to determine the accuracy of a machining centre in three dimensions. They used this measurement platform also to track thermal behaviour of a machine by repeating measurements after a certain period (45 to 90 minutes) during the heating and cooling cycle.

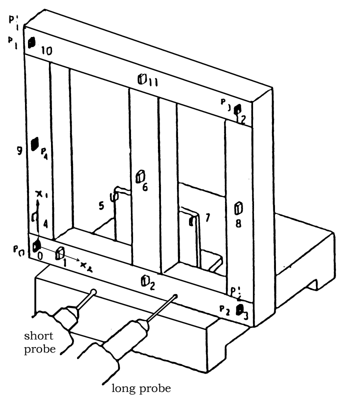


Figure 13. Metrology pallet with touch-trigger probe [Ferreira & Liu 1993]

Instead of a metrology pallet mentioned above, a hole plate can be used as a reference target [Theuws 1991, p.128]. A plate with holes at a distance of 50mm to each other was used in a study performed at the Technical University of Eindhoven. Actual distances between the holes were calibrated by PTB (Physikalisch Technische Bundesanstalt). Theuws reports that a repeatability of from 1,4μm to 7,5μm was achieved in a direction of a single axis.

A slightly revised version from the above is to use measuring probes instead of a touch trigger-probe. Thus it is possible to capture measurement data without involvement of a numerical controller. A three dimension probe has been used to measure position of precision balls located in a calibration frame [Tajbakhsh et al. 1997]. The probe consisted of three linear variable differential transformers (LVDT) assembled in 90 degree angle to each other in order to measure deviations in directions of the three axes. Two repeated measurements in one ball were used to decrease the effect of repeatability errors in this experiment.

2.1.12 Summary of measurement methods

Two categories can be found in these so called quick measurement methods; dynamic and static methods. Dynamic measurements are done in-run i.e. during motion and static measurements stop on a target point where the measurement value is captured. Touch probe with an artefact is the only device of the previously presented choices which can do static measurements only. The other devices can perform both measurement types depending on the current need and used software.

Table 1. Applicability of measurement methods

Measurement method	Positioning	Straightness	Squareness	Backlash	Cyclic error	Lateral play	Servo mismatch	Servo lag	Dynamic measurement	Accuracy
Double ball bar	⊙	○	●	●	●	●	●	●	●	B
Cross-grid encoder	●	●	●	●	●	●	●	●	●	A
Test piece measurement	●	●	●	●	○	●	●	●	●	B
Workpiece measurement [1]	⊙	●	●	●	○	●	●	●	●	C
Uni-Test	●	●	●	●	●	●	●	●	●	B
Laser tracker	●	●	⊙	●	●	●	●	●	⊙	C
Multi-beam laser	●	●	○[2]	●	●	●	○	○	●	A
Autocollimator laser	●	●	○[2]	●	●	●	○	○	●	B
Laser ball bar	⊙[3]	○[3]	●	●	●	●	●	●	●	A
Laser circular test	●	●	⊙[2]	●	●	●	●	●	●	B
Circular test with artefact	⊙	○[4]	●	●	⊙	●	●	●	●	B
Touch probe with artefact	●	●	●	●	○	●	○	○	○	B

● = Device can measure the deviation.
⊙ = Device can fairly well measure the deviation under reserve.
○ = Device cannot measure the deviation.
A = Device fits well for machine tool calibration and acceptance testing.
B = Device is adequate for daily inspections of machine tools.
C = Device can be used for daily inspections if accuracy requirement is low.
[1] = Applicability depends greatly on the complexity of a workpiece.
[2] = Deviation can be measured well with optional equipment.
[3] = 2-bar and 3-bar systems can measure these deviations well.
[4] = Rectangular features in an artefact enables measurement of straightness.

This work concentrates later mostly on dynamic measurements. Analysis of dynamic measurements is not a well studied field and thus offers yet unrevealed potential. Some comparisons, between measurement methods are presented in Table 1.
Classification of deviations is made according to terminology used elsewhere in this paper. This terminology differs to some extent from the commonly used manner, but here it is justified to sustain consistency throughout the work.
Accuracy levels are as well disputable, because exact values are difficult to give for most methods. However some classifications are made based on the given uncertainty and evaluation of the methodology. Class "A" means that this device certainly meets accuracy requirements of a machine tool inspection, if only used properly. Class "B" can be used for daily inspections without great concern towards accuracy, but tuning and compensations should be carried out based on these measurements only if trustworthiness is assured by some other means. This reliability can be tracked down for example by a previous comparative measurement between the device in question and a calibration level device. Class "C" devices can be used in everyday inspections, if reliability has been beforehand assured by comparative measurements and the accuracy requirement is not specially high. Compensations and tunings should not be done based on these measurements only.

2.2 Thermal effects

Thermal drift is the most significant single source of geometrical errors in machine tools. Thermal drift alone can cause even more than 50 % of the overall error [Weck et al. 1995]. Means to reduce this effect can be classified in three groups, which are 1.) reduction and insulation, 2.) temperature control and 3.) compensation. The two first categories are most commonly used in practise while compensation has been a popular research object. Bryan [1990] speaks for a temperature control mainly because of the difficulties in other means explained below.
Standard draft ISO/DIS 230-3 describes the methods to measure thermal drift and environmental temperature variation error (ETVE). These measurements can be used to evaluate and to quantify the thermal stability of a machine tool. Thus it is a basis for the further development in the thermal error research.

2.2.1 Reduction of thermal effects by design

The first and most important basis to make an accurate machine tool is naturally design. Design for thermal behaviour is not an exception and thus good design alone can already produce a good enough behaviour. Bad thermal design can hardly be compensated by any means at all but good design can be improved with compensation.
Heat sources can be either isolated or their power reduced in some cases. FEA (finite element analysis) is an important tool in this area to study behaviour of different structures. Different dispositions of heat sources as well as frame structures can be relatively fast examined with FEA. Lately heat pipes have been successfully used to transfer heat away from source areas [Zhang et al. 1991]. This method equalises temperature distribution and shortens consequently the warm-up time.

2.2.2 Compensation of thermal effects

All the compensation methods are based on measurement of temperature in a machine tool body or drives. This temperature information is used in different models to calculate the compensation amount. Generally only the thermal behaviour of a machine tool itself is modelled and compensated leaving effects of a workpiece and tool untouched. The modelling of a workpiece thermal behaviour is a complicated task in itself and would need a new model for each new workpiece type making thus compensation rather laborious and difficult to realise in practise. A tool is easier to model but the measurement of its actual temperature is difficult to arrange.
The first and the most simple way is to use a single temperature sensor in each axis and compensation using a linear model for each axis positioning. This schema is available in modern numerical controllers and thus it is easy to implement. Here have to be remembered that the uncertainty of the expansion coefficient of the scales and the workpiece are very high [Bryan 1990]. Temperature measurement itself involves uncertainty too and thus the overall accuracy of the compensation is low.
Recently neural networks have been used to model thermal behaviour of machine tools [Ling 1996]. This method offers a chance to use many sensors per axis and even to place them off the axis, because the calculation method itself can find out the importance of each sensor. Depending on the structure of a neural net used, the system can model also non-linearity as well as dynamic behaviour in time. The method is, however, somewhat complicated and needs an expert to tune it. Nowadays it is possible to purchase a system like this and it will be assembled later into the customer's machine.
Many studies have been made to incorporate compensation of thermal effects into a general model together with other geometrical errors. The benefit of this approach is that this way not only the positioning error in direction of an axis but as well other thermal related deviations are compensated. The model parameters are solved in continuous thermal states and then these parameters are used to compensate a machine tool [Donmez et al. 1986] [Ferreira and Liu 1986] [Theuws 1991]. Parameter estimation has to be carried out to each machine tool individually. Because of the complexity this kind of approach hasn't become popular in practise. The amount of parameters to reveal increases when different kinds of dynamic thermal states are modelled and still this kind of a method can hardly achieve good general reliability and robustness.

2.3 Analysis

The aim of analysis is to determine parametric errors from a measurement data. The analysis of measurement results can be accomplished manually, semi-automatically or fully automatically. These steps present different phases in the development of technology and calculation capacity available. Previously measurement equipment and methods offered measurement results directly. This was mainly because it wasn't possible to interpret more complicated kind of measurement results without computing power. The situation has changed with the development of computers and now there are no more reasons to use self-evident measurement methods just because they are easier to understand for a human.
The complicity of an analysis algorithm depends on the machine tool structure and measurement data presentation. It can be quite simple as in this work, when only

Cartesian three axis machine tools are considered and measurements are reduced to a plane. The work would be significantly more complex on hexapod machine tools [Soons 1997].

2.3.1 Manual interpretation

Some measurements are interpreted directly by a person without any assistance of computers. Most classical standardised measurements are analysed this way. Mainly this involves taking only a couple of discrete measurement points instead of scanning. These measurements are usually also parametric and thus reveal one deviation type at a time. This makes a human interpretation possible, but looses some information. And even though the intention is to measure just one deviation type, some other deviations can easily interfere in the measurement. Partly these restrictions are caused by measurement equipment, which doesn't have the capability of catching measurement points in high frequency.

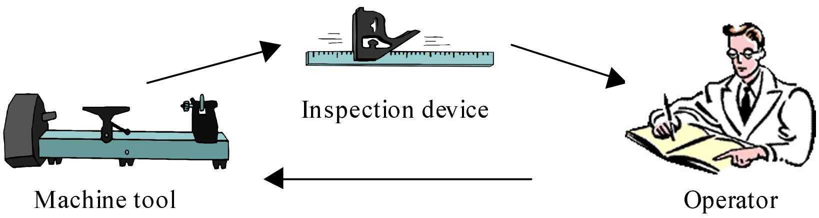


Figure 14. Human interpretation of machine tool measurements

Good examples of human interpretation are measurement of squareness and runout of a spindle (DIN 8601). We can think this is the case also when a circular test is recorded by an analogue plotter and then interpreted by a person. Also a DBB measurement recorded by a computer can be classified into this group when no further analysis is made.

2.3.2 Semiautomatic analysis

A semiautomatic analysis can find out separate deviation values and a capability value for the current tested path based on a measurement. Still some interpretation is left for the user and he must evaluate the relevance and reliability of results.

A combination of laser-interferometer measurement and generally available capture software belongs to semiautomatic analysis. It can give results for positioning accuracy and also give some uncertainty estimates for those values. But it lacks any ability to tell reasons for deviations it has observed. This can cause serious misinterpretations when some angular errors exist in a machine tool.

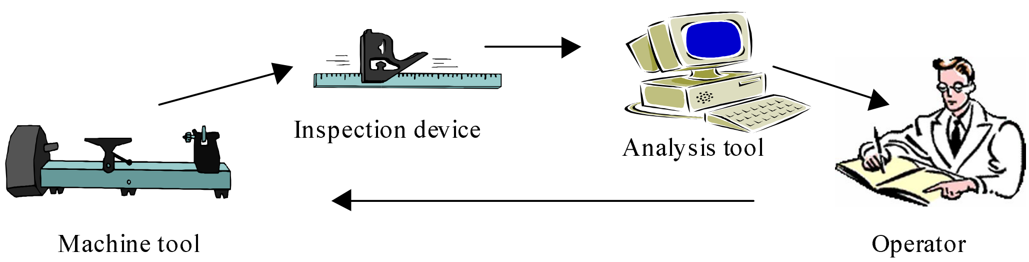


Figure 15. Semiautomatic analysis of machine tool measurements

A few pieces of analysis software are commercially available for DBB measurements. These pieces of software also belong to a semiautomatic group, because although they give some estimates of different deviation types, there is no information on the reliability of those results nor are those values put back on a numerical controller for compensation purposes.
The analysis method presented in this thesis also belongs to this group. This analysis gives results, which are ready for compensation and it also reveals the uncertainty of those estimates, but it lacks the ability to compensate machine tools automatically.

2.3.3 Full-automatic analysis

A full automatic analysis can find out deviation values and also estimate their reliability. It can ask for an additional measurement with new parameters when needed to ensure the reliability of results. This type of an analysis can still work only in one plane, though it causes higher uncertainty values for deviation estimates. Therefore a three dimensional analysis is preferred.
Full-automatic analysis can either do the compensation itself or it can offer compensation information, which can be activated without a human intervention. Compensation can be performed either by a machine tool controller itself or it can be done before by a postprocessor of an off-line NC-programming tool.

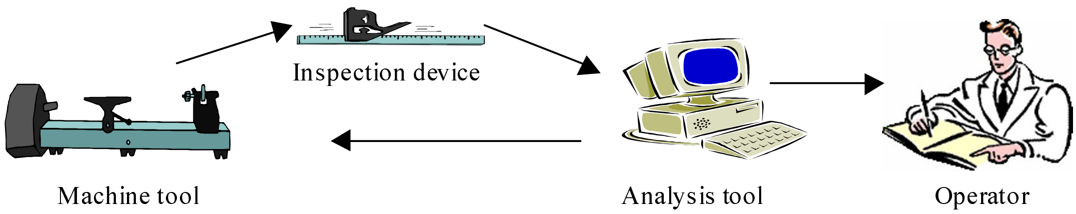


Figure 16. Full-automatic analysis of machine tool measurements

This type of analysis is needed for flexible manufacturing systems, because it makes it possible to measure machine tools between workpieces without interruptions. Measurements could even be completed at night after all the scheduled pieces are machined and thus loose no valuable machine time at all. The analysis and compensation cycle could be realised without interruption in production. Because of the shortened measuring time frequent tests are feasible. This again keeps machines in control all the time and also narrows the deviation range.
Currently there are no available measuring equipment nor analysis software in this level. However, this will become possible in the near future, because analysis methods

have been developing lately and, on the other hand, flexible manufacturing systems have become more common. Because those systems are expensive and intended to be used 24 hours a day, it is important that they can be utilised during the maximum time and that they are producing high quality all that time. This means full-automatic measurement, analysis and compensation.

2.3.4 Analytic geometry notation

The first method to represent errors of a machine tool has been geometrical approach [Love and Scarr 1973]. Compared to the Denavit-Hartenberg method presented below, this notation can lead to long equations if the whole machine is modelled at once.

The basic principles of this method are however solid, but the problems are more related to cumbersome notation of a solved problem. Because a more convenient method has been found, this older way has been forgotten. The basic formulae of geometrical notation are however more intuitive and also they can be flexibly used with different conditional statements.

The work presented later is based on geometrical notation. Also because the whole analysis works just in a plane, the complicity of solved equations is no issue at all. Conditional statements used in latter equations take into account changes in the feedrate and motion direction.

2.3.5 Denavit-Hartenberg notation

A systematic approach to model lower-pair mechanisms, called Denavit-Hartenberg (D-H) notation [Denavit and Hartenberg 1955], has been successfully used in robotics and also in machine tool measurements. Most of the recent work has been based on this theory, because notation offers good tools to model straight and inverse kinematics.

Matrix notation supports translations along axis and angular turn around joints. A joint is coupled with an arm and a single matrix presents this pair. This method supports well three-dimensional systems and it can model also errors in joints and arms. Straight kinematics from joint values to an actual position of a tool point is well behaving and easy to calculate. However, inverse kinematics is in most cases complicated to evaluate analytically and that is why different approximations are widely used.

Because D-H notation does not natively use different parameters depending on motion direction, nor do the developed methods based on D-H, support that. Thus the systems are insensitive to different kinds of reversal errors. Neither do the systems have speed dependent parameters, which hampers detection of servo based errors. These deficiencies are not actually Denavit-Hartenberg’s fault, but taking these matters along would force one to split calculations in many parts depending on motion parameters.

Even if modelling a machine is rather a straight forward process by using D-H notation, it can hardly be expected that this modelling could be implemented in ordinary machine shops. However, good results have been reported in the US in the mid 80’s [Ferreira and Liu 1986] [Donmez et al 1986]. Research groups tested the system in laboratory conditions and achieved remarkable enhancements in accuracy. The both groups had integrated a thermal compensation in their algorithms. However, thermal compensation didn’t take advantage of D-H, it was merely a pure positioning

correction added to the global model. Donmez claims that this kind of an integrated algorithm can give accuracy enhancements up to 20 times.
More thorough explanation on using rigid body kinematics with D-H notation was completed for three axes machines [Andersson 1992] and for five axes machines [Theuws 1991][Soons et al. 1992]. Theuws integrated a thermal compensation in his system and got rather good results (i.e. 50% reduction in geometrical errors and in thermal errors more than 50%). However, he points out that the measurements needed for this method are really laborious and that many complicated issues are involved in thermal compensation. Because of the many parameters and unknown variables in the thermal stage of a machine tool, Andersson has concluded to recommend making measurements in a thermal stage which corresponds to normal machining situation. Based on the analysis model a whole follow-up system of a machine tool has also been proposed [Figure 17].

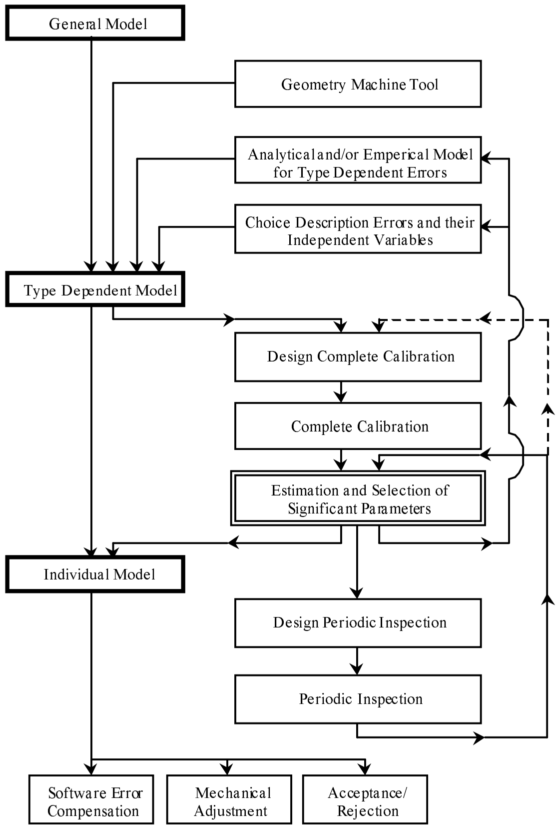


Figure 17. A machine tool's quality control system with respect to its quasistatic errors [Soons et al. 1992]

2.4 Compensation and adjusting

Analysis results of deviations of a machine tool should be used to adjust the machine to produce better quality. These actions can be called either adjustments or compensations. Adjustments change the parameter values in a controller or in a machine tool itself. Compensations instead are additional corrections, which are added to target positions.

2.4.1 Adjustments

Numerical controllers offer a possibility to adjust servos by parameters. Thus it is possible to adjust servo mismatching and also, to certain extent the servo lag automatically. However, because many factors are involved in servo tuning the values should not be changed without careful consideration. Thus even if the analysis method can reveal this type of deviations, they are not applicable for full-automatic adjusting.

Manual adjusting is needed to reduce some geometrical deviations. The smoothest and the best way to reduce the squareness and clearance error is to adjust them manually, even if means also to compensate them exist. Manual adjusting was earlier needed to tune servos, too.

Adjustments and compensations cover partly equivalent deviations. Nevertheless these methods are not mutually exclusive. Compensations can be used to fine tune remaining amount of deviation after adjustment.

2.4.2 Compensation

Compensation of a machine tool path can be realised by compensation tables, by an external correction of a feedback value and by modifying an NC-program. All the methods have been used to some extent, but compensation tables are the most common.

Compensation requires always some computing time, which has this far effectively hindered implementation of sophisticated compensations. However situation has changed lately and now a great variety of compensation methods is available. The superiority of a compensation method can be determined by looking at compensation interval, renewal time and resolution. Ease of use, management of compensations, information flow and compatibility with other systems are important parameters when choosing a compensation method.

2.4.2.1 Compensation tables

Compensation tables are stored in the numerical controller. Look-up type tables have compensation amounts stored at certain intervals. Depending on the controller type compensation values between the stored points are either interpolated linearly or the whole interval has a fixed value [Figure 18]. Compensation can either correct the same axis, which determines the look-up position in the table or some other axis. This enables compensation of squareness error. Tables of their own can be determined for both motion directions, which is used to compensate reversal errors.

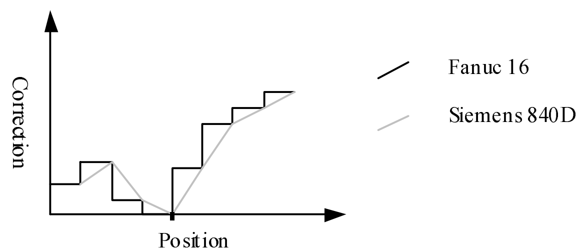


Figure 18. A look-up table

Because compensations are stored in a controller, some benefits are being gained. Firstly, servo algorithm is adapted with compensations and thus the existence of compensations does not deteriorate the dynamic performance of the servo system. Secondly, the compensation algorithm is all the time aware of real motions of a machine tool (speed, direction) and thus can use the exactly right compensation model. And last, but not least, the combination of a controller and a machine tool is an independent unit, which has a standardised interface (NC-program) to an upper level.
Tables can be updated also during the run-time without a power-up or reset. Theuws [Theuws 1991] used this property to compensate thermal effects in real time. This enables also automatic compensation of geometric errors.

2.4.2.2 External correction of the feedback value

If compensation tables are not available or requirements for compensation are so high that tables are not adequate, it is possible to build an external compensation unit, which adjusts feedback values to the controller. This system can easily involve both geometrical and thermal compensations [Donmez et al 1986].
This practice offers great flexibility, but it has some drawbacks. Even if the servo loop performance is not directly deteriorated, the living feedback makes the tuning of servo parameters difficult. If new compensation values are not calculated with the same frequency as new position loop target values, unexpected servo behaviour can occur.
Because this kind of a system can strongly reduce the dynamic capability of a machine tool, it is not likely this system will become more common. However, it can be very useful in laboratory conditions when new compensation methods are tested.

2.4.2.3 Modification of a NC-program

A NC-program can be modified in such a way that the errors observed in a machine tool are compensated when the program is run [Takeuchi and Watanabe 1992][Spaan 1995][Mahbubur et al 1997]. The benefit of this method is that it is applicable also to older controllers. However, this method has also some drawbacks, which hinders it to become a primary choice for compensation purposes. Firstly, lines in a NC-program must be split in many smaller lines thus increasing the program size. Secondly, a numerical controller has difficulties to shift between these new lines, because it tries to achieve all the new corner points. Thirdly, administration of right versions of NC-programs can easily become difficult to handle.
A new NC-program coding method with NURBS (Non-Uniform Rational B Spline) etc. can help to exploit this method. However, this cannot be seen to be a native compensation method for numerical controllers, but can be applicable to some special tasks.

3 MATHEMATICAL MODEL

3.1 Introduction

Raw measurements of machine tools themselves do not reveal errors of machine tools. Some kind of a method is needed to find out separate deviation values and to make different kinds of measurements comparable with each other. These separate values can then be used to follow-up and diagnose machine tools. This calculation should be automatic and reliable to be able to serve higher functions with right information.

3.2 Tasks

The calculation model includes different tasks to complete. These actions prepare raw measurement data for analysis and also estimate sensitivity of results. Analysis can be divided into the following tasks:

1. classify array of measurement points to analysis features
2. carry out possible co-ordinate transformations
3. do rough filtering of measurement data
4. evaluation of deviation values
5. estimation of the accuracy of results.

These tasks are dependent on the actual analysis method used, but in some way each method has to handle these tasks. It is more a question of calculation and functions used to perform those tasks.

3.3 Methods

The calculation method for the evaluation of deviation values must be chosen between different search algorithms and the analytical solution. Widely used search methods are neural networks, genetic algorithms and traditional stepping search algorithms. When an analytical solution is attainable, it offers a more accurate result compared to different search algorithms. Secondly, computing time is commonly shorter for an analytical model. Because of this the analytical model is always preferred when it just is possible to achieve.

3.3.1 Analytical model

When a process model is non-linear, it is generally very complicated to find an analytical solution. In those cases a general approach is to linearise a model in the operating point. This offers a relatively simple calculation for a solution with a price of limited solution space. It is sometimes also possible to resolve an original non-linear equation offering exact solutions in the whole parameter space. Unfortunately this is possible only in rare cases and it is also laborious. This thesis presents a linearised model, which gives reliable results with normal machine tools [chapter 1.7]. The fitting procedure is an essential part of the analytical solution. The most common method is to use least-squares fitting, which is used in this work, too. The benefit of least-squares is that it is fast and reliable to compute and solutions are generally

robust. The biggest drawback, that is commonly presented, is that it minimises the error, which does not have clear physical background thus not being relevant to the problem. However least-squares fitting works well to give a good average result, but cannot tell or restrict the maximum error.
The Chebyshev norm has also been used to evaluate deviation parameters in some cases [Tajbakhsh et al. 1997]. This fitting minimises the maximum error and is thus theoretically the best fitting procedure. It doesn't necessarily give the best result in average, but it gives a value for the maximum error and also minimises it. There is a drawback though that the method is very sensitive to measuring errors and noise. Thus it requires filtering. Filtering on the other hand can cause similar problems in authenticity as mentioned earlier with the least-squares fitting.
If repeatability of machine tools is on a level later reported in this work, there is no practical difference in accuracy between fitting methods. The question is merely computational and of reliability. Some other studies [Takamasu et al. 1998] as well have recommended the use of the least-squares method in order to separate features from CMM measurements. Thus the least-squares method is here the choice, because it offers the highest efficiency.

3.3.2 Genetic algorithms

A genetic algorithm can vary itself by two different methods: mutation and inheritance. Inheritance combines properties of two predecessors. Mutation is a random change in parameters. Hereby this method uses inheritance to search a local minimum and mutation jumps around the parameter space to find a new global minimum search start point. The method has been found to be useful in cases with a very large parameter space and difficult non-linear equations.

3.3.3 Neural networks

Neural networks are multi-layer modellers, which combine non-linear transfer functions with a linear summa. A layer consists of cells, which each first add values from cells of a preceding layer with an individual weight and then this sum is put through a transfer function. The most intelligent part of these methods is the system to tune weights for cells. This kind of a system can model also non-linearities. It fits for problems with unknown underlying equations, a quite large parameter space and moderate accuracy requirements.
A previous research has been made earlier to compare neural nets to an analytical model in a double ball bar analysis. The study comes to the conclusion that when an analytical model is available it can offer better results than a neural net. [Torvinen et al. 1995]
Generally neural nets are used in the cases in which dependencies and functions from initial values to observation are unknown or especially difficult. There are many cases in which these dependencies are known in theory, but in practise the application of them is so complicated that neural nets are used to model the behaviour. However, the rule of thumb is that neural nets should be used only when analytical methods are not applicable. Because a neural net structure does not really know the behaviour behind a phenomenon it cannot give as good results as a good analytical model does.

3.3.4 Search algorithms

Traditional search algorithms stride over the parameter space using a known linear or non-linear function trying to find a global minimum or maximum depending on requirements. The search algorithm can either use real derivative information of the underlying function, estimate a derivative with two subsequent points or neglect a derivative. Search algorithms are effective solution providers when an analytical solution is not achievable for some reason. Weaknesses of these methods are that they can find just a local solution and that computing time cannot be estimated and it can be rather long.

3.4 Modelling of deviations

3.4.1 Principles

The analysis is based on the use of features. Every measurement is first split into features and then they are handled the required way. Original measurement data is first split into features, transformed to a local co-ordinate system, deviation prototypes are built for each feature and deviation and the prototypes are then fit to the transformed measurement.

3.4.2 Modelling

Before individual features can be distinguished the measured paths have to be known. This can be achieved either by drawing measurement paths in an analysis program or by importing them from a measurement program file, for example DMIS (Dimensional Measuring Interface Standard) [ANSI/CAM-I 1995].
The measurement path is just one side of the modelling information needed, because the manufacturing information is also required. Again this can be modelled in the same way as the measurement paths above. At least machining directions, tools, positioning on the machine tool table and feedrates have to be modelled in the machining information database.

3.4.2.1 Features

The types of features handled by the analysis are restricted, because every feature handled needs its own kind of formulae. In this thesis work only features in one plane are studied. The features used are line, arc and point. Information required by the features is presented in table 1.

Table 2. Feature information

Arc	Line	Point
Order number	Order number	Order number
Plane	Plane	Plane
Feedrate	Feedrate	Feedrate
Tool	Tool	Tool
Centre point x,y,z	Start point x,y,z	Position x,y,z
Radius	Length	Bore hole radius
Direction	Angle	
Start angle	Approach angle	Approach angle
Stop angle		
Material side	Material side	

3.4.3 Feature separation

Measurement data is commonly just a long list of co-ordinates without information on where it was obtained. CMM measurement results are originally stored by features, but this information is easily lost when transporting measurement in a compatible data-file format. The cross grid encoder measurement does not even have this information, because it is just a time based capturing device without any knowledge of the actual measured shape.

The method uses recognition zones [Figure 19] to separate points belonging to each feature. If a point hits in a start zone of the first feature, a collection of data points for this feature is started. The collection will continue until a point in the end zone of a feature is found. This starts a search of a start zone of the next feature. This continues until all the features are collected.

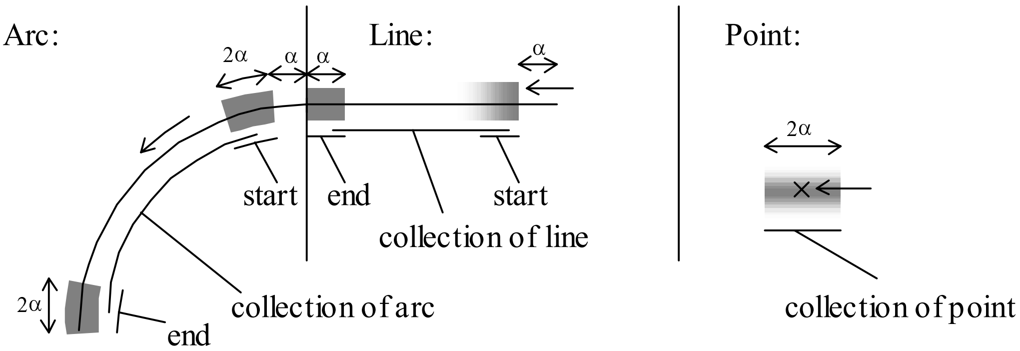


Figure 19. Recognition zones

A predefined constant α, recognition length, is used to determine the length of recognition zones. The recognition length depends on the data point interval and the centring of a measurement. The higher the capture frequency and the better the centring, the smaller can the recognition length be. Too small a recognition length causes loosing of features (and furthermore failure of analysis) because no points hit in a zone and a too long one lets unnecessary many points to be neglected.

A point is determined to locate in a position where two successive points in a collection area of the point are closest to each other. The average of those two

measuring points is used later to stand for as the real location of the point. A point in CMM measurements is presented by a bore hole. The hole is recognised by an arc recognition system and the point location is interpreted to be the centre point of a calculated least squares circle.
The feature recognition leaves always some measurement points from the start of a line or an arc neglected. This looses information on the behaviour of a machine and that is why too long recognition zones should be avoided. On the other hand the analysis presented in this thesis concentrates on low frequency geometric errors and thus transients occurring just in a switch of features can disturb the analysis algorithm. With this in mind, it is more advisable to write off some points right at the start of a feature.

3.4.4 Internal data format

The measured data can be read in Cartesian co-ordinates. Yet, this format is not suitable for analysis and it has to be reduced to a difference between a target form and a measured path only. This preparation makes it possible to use the least squares method presented later.
This reduction is implemented in arcs by calculating for every measurement point the difference between the measured point and the target point in the direction of the radius. The difference between the measured point and the target point in the direction of the normal of the line is used for lines. But for points we use the distances in the direction of both Cartesian axes instead.

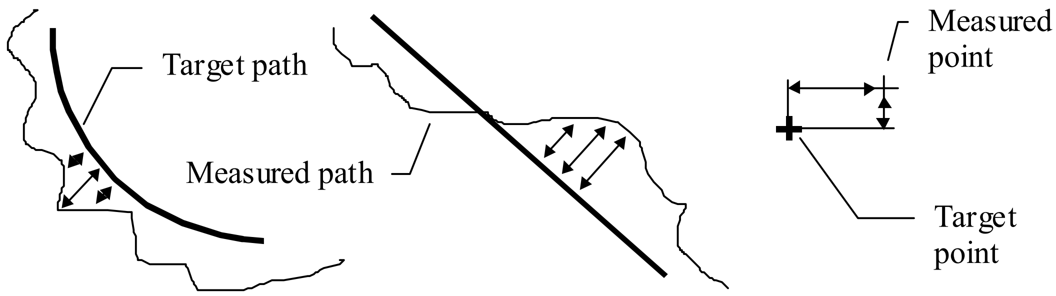


Figure 20. Measurement deviation [Hölsä 1997a]

In addition to the measurement deviation also the position within the form has to be calculated. So for arcs this is the angle for the measurement point, for lines it is the position on the line from the starting point and for points it is neglected. These are needed later when calculating deviation prototypes for the measurement analysis.

3.5 Analysis of deviations

An own kind of behaviour can be found for every deviation type. They are also reflected differently on each feature type. The first thing needed to start the analysing work is to find the formulas, which characterise these phenomena. The following kinds of machine tool deviations are considered in the analysis:

- Backlash
- Cyclic error
- Lateral play
- Linear scaling error
- Servo mismatch
- Servo lag
- Straightness (2^{nd})
- Squareness
- Measurement offset
- Measurement rotation
- Tool compensation
- Up milling deflection

The deviation types to be analysed have been selected among the deviations commonly found in machine tools. The selected deviations are of great importance for the quality capability of a machine tool, they possess a regular deviation path and are distinguishable from each other in favourable conditions. However, there are no major obstacles to prevent taking other deviation types in analysis as long as they have a regular deviation path and are distinguishable with used measurement methods. The deviation description here is mainly based on the work done for a double ball bar measurement analysis in Kakino's laboratory, Kyoto Japan [Kakino et al 1993].
The three last deviations, measurement offset, rotation and tool compensation, don't tell any information on the condition of a machine tool. Yet they have to be calculated, because otherwise the analysis process would try to explain those errors with real deviations of a machine tool. Thus these deviations are measurement - not machine tool - specific.

3.5.1 Description of deviation types

3.5.1.1 Backlash

Backlash is an error motion occurring because of a clearance in a transmission and lost motion caused by an elastical deformation of a driving mechanism. This deviation type includes thus, indeed, two different type of error sources. Clearance is constant regardless of speed, acceleration and forces, whereas the lost motion is dependent on the force aimed at a transmission [Kakino et al 1993]. The direction of the error is opposite to the motion direction. If the deviation amount is negative, this deviation is usually caused by too big a backlash compensation value in a numerical controller.
Pitching of an axis causes also motion, which looks like backlash. The amount of a deviation caused by pitching increases further away from the pivot point. This fact can be used to detect pitching when suspected.

3.5.1.2 Cyclic error

Cyclical deviation can be caused either by an error in a ball screw with an interval of a ball screw pitch (drunkenness) or a misalignment of a transmission system when rotary encoders are used. Generally no cyclical error can occur if linear encoders are used. The direction of the error is parallel to the direction of the axis having an error source.

3.5.1.3 Lateral play

When an angular error is present in an axis, it causes deviation, named here lateral play. Lateral play is dependent on the motion direction and its direction is normal to the axis causing the error. Lateral play can most reliably reveal the rolling of an axis. In this case the amount of the deviation increases the further away the measurement plane is from the pivot point.

Yawing of an axis can also cause lateral play in some cases, but it depends on the distance between the measurement setting and the pivot point. Generally lateral play doesn't reliably detect the existence of a yawing.

Pitching is not detected by a lateral play, but it can be seen in a backlash value.

3.5.1.4 Linear scaling error

Uniform expansion or contraction of a motion of a machine tool can occur, if a ball screw warms up in a machine equipped just with rotary encoders or a linear scale expands because of heat. The expansion here is a linear deviation and thus presumes constant warm rise all along the measurement. The direction of the deviation is parallel to an axis having the error.

It is typical for linear scales to have some amount of scaling error when installed in a machine tool because of tensions in fixing and difference in temperature compared to calibration conditions. In some scales this expansion or contraction can be adjusted mechanically, but it can also be adjusted by parameter changes in a controller.

The ball screw is mounted with a pre-tension and this should absorb the thermal expansion effect. However, it is possible that sometimes pre-tension is not tight enough and thus warming up of a screw causes error in machines, which have rotary encoders only assembled at the end of a ball screw or a servo motor.

3.5.1.5 Servo mismatch

When the position loop gains for the two axes are not equal, mismatching of servos occur. Then the more rigid axis moves ahead of the other one and it causes bad following of a circular path. The problem is especially difficult when the weights of the axes are greatly different, because in that case it is very difficult or even impossible to tune both axes equally. When seeking this, the tuning can either end up in oscillation or sluggish total performance.

3.5.1.6 Servo lag

It is characteristic for a servo system that it has some lag to a commanded position. This lag is the bigger the higher the speed is. Thus circular paths will remain too small with high feedrates and a small radius. Increasing of a position loop gain will reduce this deviation, but it has other restrictions, which usually limits adjustments.

A feed-forward control eliminates this deviation when used at 100%. Feed-forward is not, however, available in all controllers and even where it exists it's not always possible to use it at 100%. This is because of limitations in the calculation power of a controller and rigidity of a machine tool. Nevertheless this is a powerful tool to reduce servo lag.

3.5.1.7 Straightness

Straightness of the guide ways can differ many ways from an ideal straight line. The model uses, however, only a second order curve to model the straightness error. This can explain only major straightness errors, leaving higher frequency variations neglected. It is a compromise between modelling reality and total reliability of the analysis system. The outcome is that the model can reveal problems in the straightness of the guide ways, but it cannot tell exactly how much and where the problems lie.
Straightness deviation points out in the direction of normal to the axis having the straightness error.

3.5.1.8 Squareness

Squareness error is a non-perpendicularity between the two axes tested. A bad assembly of a machine, poor machining quality of the parts of a machine tool or a collision can cause this deviation. This is thus a structural problem and can be adjusted either mechanically or using compensation tables in a numerical controller.
The sagging of an axis, usually a spindle head, causes also the same kind of a phenomenon. The deviation path is not exactly the same as it is for a squareness error of the axes supported in the both ends or the whole length, but the method will explain this deviation by giving a higher value for a squareness deviation.

3.5.1.9 Measurement offset

When measuring either directly a machine tool or a test piece, a theoretical zero point doesn't hit exactly in the same point with the real fitted zero point. Measurement data is transferred to a theoretical zero point to make data visually more pleasing to look at.

3.5.1.10 Measurement rotation

Like the measurement offset just before, a rotational orientation of a measurement doesn't automatically agree with the theoretical one. Rotation angle is used likewise to turn the measurement data into a more suitable position for the visual interpretation.

3.5.1.11 Tool compensation

Differences in a tool radius can be caused by bad presetting of a milling tool or into a smaller extent by the errors in the measuring probe calibration. This deviation exists only in machined pieces, direct measurements do not have this deviation type at all. Like the two previous deviations, also this is just a measurement specific issue and doesn't reflect any problems of a machine tool.

3.5.1.12 Up milling deflection

Machining of test pieces includes both down- and up milling. Depending on the tool, raw material and machine tool itself can milling mode cause different deflections. We make the assumption that this deflection is similar to the direction of both axes and it depends solely on the milling mode. This deviation type doesn’t exist in direct measurements.

3.5.2 Fitting

The deviation prototypes are combined in the format of a matrix, which will be fitted to the measurement data. When collecting this matrix it has to be tested if the matrix is linearly dependent after each deviation type vector. If this is the case this type of deviation cannot be analysed and it is removed from the matrix. Then the next deviation type is added to the matrix and tested. This is repeated for every deviation type. The final prototype matrix can be presented as:

$$A = \begin{bmatrix} \underline{p}_{dev1} & \cdots & \underline{p}_{dev\_n} \end{bmatrix} \tag{1}$$

Now it is possible to calculate the estimates for deviations $\underline{d}$ collected in a vector in the same order as we collected deviation prototypes for the matrix A. The estimation is based on the use of the least-squares fitting, which is justified in chapter 3.3.1. When the measured difference to the target path is marked as $\underline{m}$, we will get the following kind of a formula:

$$\underline{d} = A^{\dagger} \underline{m} \tag{2}$$

Here † means pseudoinverse. If we assume that all the data points have the same variance s^2 and that they are also independent, we can use the following formula to estimate the uncertainty of our results:

$$V = (A^T A)^{-1} s^2 \tag{3}$$

The assumption of independent points and equal deviation in each point do not fully meet reality, but the value achieved using this formula can however estimate the reliability of results. It is more just for an internal use of a method than to be shown for a user as a final estimate of the reliability.
It is more secure to include also external sources of error in the estimation of reliability. Practical experiments should be done to reveal the real reliability of a method and this value can later be used as the final reliability of the method.

3.5.3 Prototypes

Notation for individual deviation types for arcs is largely based on the work of Kakino [Kakino 1993]. Additions made for this system are rotation, tool compensation, up milling deflection and servo lag. Notation of vectors and points is made just for this system, but it naturally inherits principles from handling of arcs [Hölsä 1997c]. The formulas presented, use the following notation:

- i Measurement point number
- t Feature number
- f_t Feedrate on the feature t
- l_x The half of the total width of the measurement along the 1st axis

3.5.3.1 *Prototypes for arcs*

The formulas used to calculate the deviation prototypes for arcs are presented here for x-axis using the notation:

R_t	Radius of the circle *t*
$x_{0,t}$	Centre point of the circle *t*
x_0	Centre point of the measurement
dir_t	{1 if counter-clockwise | -1 if clockwise}
θ_i	Angle at a measurement point *i*

These formulas can be generalised to other axes just by replacing the equivalent variables with their counterparts.

Centring:

$$p_{arc\_centringx}(\theta_i) = \cos(\theta_i) \tag{4}$$

Rotation:

$$\begin{aligned} x_i &= \cos(\theta_i)\cdot R_t + x_{0,t} - x_0 \\ y_i &= \sin(\theta_i)\cdot R_t + y_{0,t} - y_0 \\ p_{arc\_rotation}(\theta_i) &= \sqrt{x_i^2 + y_i^2}\cdot\cos\big(\theta_i - \text{atan}(y_i, x_i)\big)\Big/\sqrt{l_x^2 + l_y^2} \end{aligned} \tag{5}$$

Tool compensation:

$$p_{arc\_tool}(\theta_i) = \{1 \text{ material outside} \mid -1 \text{ material inside}\} \tag{6}$$

Up milling deflection:

$$p_{arc\_uplling}(\theta_i) = dir_t \tag{7}$$

Squareness:

$$p_{arc\_squareness}(\theta_i) = \cos(\theta_i)\cdot\big(\sin(\theta_i)\cdot R_t + y_{o,t} - y_o\big)/\, l_y \tag{8}$$

Scale error:

$$p_{arc\_scalex}(\theta_i) = \cos(\theta_i)\cdot\big(\cos(\theta_i)\cdot R_t + x_{o,t} - x_o\big)/\, l_x \tag{9}$$

Straightness:

$$p_{arc\_straightness}(\theta_i) = \sin(\theta_i)\cdot\Big(\big(R_t\cdot\cos(\theta_i) + x_{0,t} - x_0\big)^2\Big/ l_x^2 - \tfrac{1}{3}\Big) \tag{10}$$

Backlash:

$$p_{arc\_backlashx}(\theta_i) = \begin{cases} dir_t \cdot \cos(\theta_i) & \text{, when } \theta_i \in (0,\pi] \vee \theta_i \in (2\pi, 3\pi] \\ -dir_t \cdot \cos(\theta_i) & \text{, when } \theta_i \in (-\pi, 0] \vee \theta_i \in (\pi, 2\pi] \end{cases} \quad (11)$$

Variable backlash:

$$p_{arc\_bl\,\mathrm{var}\,x}(\theta_i) = \begin{cases} dir_t \cdot \cos(\theta_i) \cdot \left(R_t \cdot \cos(\theta_i) + x_{0,t} - x_0\right) / l_x & \text{, if } \theta_i \in (0,\pi] \vee \theta_i \in (2\pi, 3\pi] \\ -dir_t \cdot \cos(\theta_i) \cdot \left(R_t \cdot \cos(\theta_i) + x_{0,t} - x_0\right) / l_x & \text{, if } \theta_i \in (-\pi, 0] \vee \theta_i \in (\pi, 2\pi] \end{cases} \quad (12)$$

Lateral play:

$$p_{arc\_playx}(\theta_i) = -dir_t \cdot \left|\sin(\theta_i)\right| \quad (13)$$

Servo mismatch:

$$\begin{aligned} f_{max} &= \max_t(f_t) \\ p_{arc\_servo}(\theta_i) &= -dir_t \cdot f_t \cdot \sin(2\theta_i) / f_{max} \end{aligned} \quad (14)$$

Cyclic deviation:

$$\begin{aligned} p_{arc\_cyclicx1}(\theta_i) &= \cos(\theta_i) \cdot \sin\left(\left(\cos(\theta_i) \cdot R_t + x_{o,t}\right) \cdot 2\pi / pitch_x\right) \\ p_{arc\_cyclicx2}(\theta_i) &= \cos(\theta_i) \cdot \cos\left(\left(\cos(\theta_i) \cdot R_t + x_{o,t}\right) \cdot 2\pi / pitch_x\right) \end{aligned} \quad (15)$$

To use these formulas, a value for the cyclic deviation pitch ($pitch_x$) has to be determined beforehand. The results can be converted after fitting to a more understandable form by using the formula for a magnitude and a phase:

$$\begin{aligned} d_{cyclicx\_mag} &= \sqrt{(d^2_{cyclicx1} + d^2_{cyclicx2}} \\ d_{cyclicx\_phase} &= \mathrm{atan}(d_{cyclicx2}, d_{cyclicx1}) \end{aligned} \quad (16)$$

Servo lag:

$$\begin{aligned} fr_{max} &= \max_t\left(f_t^2 / R_t\right) \\ p_{arc\_servolag}(\theta_i) &= f_t^2 \cdot fr_{max} / R_t \end{aligned} \quad (17)$$

3.5.3.2 Prototypes for lines

The specific variables used for lines are:

- α_t The angle of line
- φ_i The position on the line
- $x_{0,t}$ Starting point of the feature *t*

Because the cosine and sine functions are needed in most deviations the following notation is used:

$$fx_t = \cos(\alpha_t) \qquad fy_t = \sin(\alpha_t) \tag{18}$$

Centring:

$$p_{line\_centringx}(\varphi_i) = fy_t \tag{19}$$

Rotation:

$$\begin{aligned} x_i &= fx_t \cdot \varphi_i + x_{0,t} - x_0 \\ y_i &= fy_t \cdot \varphi_i + y_{0,t} - y_0 \\ p_{line\_rotation}(\varphi_i) &= -\sqrt{x_i^2 + y_i^2} \cdot \sin\left(\mathrm{atan}(y_i, x_i) + \tfrac{\pi}{2}\right) \Big/ \sqrt{l_x^2 + l_y^2} \end{aligned} \tag{20}$$

Tool compensation:

$$p_{line\_tool}(\theta_i) = -\{1 \text{ material on the left} \mid \text{ -1 material on the right}\} \tag{21}$$

Up milling deflection:

$$p_{line\_upmilling}(\theta_i) = 1 \tag{22}$$

Squareness:

$$p_{line\_squareness}(\varphi_i) = fy_t \cdot \left(fy_t \cdot \varphi_i + y_{0,t} - y_0\right) \Big/ l_y \tag{23}$$

Scale error:

$$p_{line\_scalex}(\varphi_i) = fy_t \cdot \left(fx_t \cdot \varphi_i + x_{0,t} - x_0\right) \Big/ l_x \tag{24}$$

Straightness:

$$p_{line\_straightnessx}(\varphi_i) = -fx_t \cdot \left(\left(fx_t \cdot \varphi_i + x_{0,t} - x_0\right)^2 \Big/ l_x^2 - \tfrac{1}{3}\right) \tag{25}$$

Backlash:

$$p_{line\_backlashx}(\varphi_i) = -\operatorname{sgn}(fx_t) \cdot fy_t \tag{26}$$

Variable backlash:

$$p_{line\_bl\,\mathrm{var}\,x}(\varphi_i) = -\operatorname{sgn}(fx_t)\cdot fy_t \cdot \left(fx_t \cdot \varphi_i + x_{0,t} - x_0\right)\big/ l_x \tag{27}$$

Lateral play:

$$p_{line\_playx}(\varphi_i) = -\left|fx_t\right| \tag{28}$$

Servo mismatch:

$$\begin{aligned} f_{max} &= \max_t\left(f_t\right) \\ p_{line\_servox}(\varphi_i) &= 2\cdot fx_t \cdot fy_t \cdot f_t / f_{max} \end{aligned} \tag{29}$$

Cyclic error:

$$\begin{aligned} p_{line\_cyclicx1}(\varphi_i) &= fy_t \cdot \sin\left(\left(fx_t \cdot \varphi_i + x_{0,t}\right)\cdot 2\pi \big/ pitch_x\right) \\ p_{line\_cyclicx2}(\varphi_i) &= fy_t \cdot \cos\left(\left(fx_t \cdot \varphi_i + x_{0,t}\right)\cdot 2\pi \big/ pitch_x\right) \end{aligned} \tag{30}$$

Servo lag is neglected for lines.

3.5.3.3 Prototypes for points

The specific variables used for points are:

- β_t The approach angle of the point
- $x_{0,t}$ Position of the point t
- i Index for deviation in the direction of the 1st axis
- $i+1$ Index for deviation in the direction of the 2nd axis

Because the cosine and sine functions are needed in most deviations they are marked in the following way:

$$\begin{aligned} fx_t &= \cos(\beta_t) \\ fy_t &= \sin(\beta_t) \end{aligned} \tag{31}$$

Centring:

$$p_{po\,\mathrm{int}\_centringx}(i) = 1 \tag{32}$$

Rotation:

$$\begin{aligned} x_i &= x_{0,t} - x_0 \\ y_i &= y_{0,t} - y_0 \\ p_{point\_rotation}(i) &= \sqrt{x_i^2 + y_i^2}\cdot \cos\left(\operatorname{atan}(y_i, x_i) + \tfrac{\pi}{2}\right)\Big/\sqrt{l_x^2 + l_y^2} \\ p_{point\_rotation}(i+1) &= \sqrt{x_i^2 + y_i^2}\cdot \sin\left(\operatorname{atan}(y_i, x_i) + \tfrac{\pi}{2}\right)\Big/\sqrt{l_x^2 + l_y^2} \end{aligned} \tag{33}$$

Squareness:

$$p_{point\_squareness}(i) = \left(y_{0,t} - y_0\right)/l_y \tag{34}$$

Scale error:

$$p_{point\_scalex}(i) = \left(x_{0,t} - x_0\right)/l_x \tag{35}$$

Straightness:

$$p_{point\_straightnessx}(i+1) = \left(x_{0,t} - x_0\right)^2 / l_x^2 - \tfrac{1}{3} \tag{36}$$

Backlash:

$$p_{point\_backlashx}(i) = -\operatorname{sgn}(fx_t) \tag{37}$$

Variable backlash:

$$p_{point\_blvarx}(i) = -\operatorname{sgn}(fx_t) \cdot \left(x_{0,t} - x_0\right)/l_x \tag{38}$$

Lateral play:

$$p_{point\_blvarx}(i+1) = \operatorname{sgn}(fx_t) \tag{39}$$

Cyclic error:

$$\begin{aligned} p_{point\_cyclicx1}(i) &= \sin\left(x_{0,t} \cdot 2\pi / pitch_x\right) \\ p_{point\_cyclicx2}(i) &= \cos\left(x_{0,t} \cdot 2\pi / pitch_x\right) \end{aligned} \tag{40}$$

Tool compensation, up milling deflection, servo mismatch and servo lag are neglected for points.

3.6 Reliability

The reliability of the results is a crucial issue, because the method is sensitive to noise and different measurement methods can give slightly different results. The user should get an estimate of reliability for each result to be able to better comprehend the real relevance of it.

Reliability here means uncertainty of the method. Uncertainty is composed of uncertainties of the calculation itself and uncertainties of a measurement and a machine tool. Uncertainties are here classified into two categories. Inner uncertainty consists of uncertainties arising from the calculation and the analysis method principles. External uncertainties are caused by the measurement method, measuring device, natural variation of a machine tool, and material etc.

3.6.1 Inner uncertainty

3.6.1.1 Deficient analysis

The analysis method can explain just a couple of different deviation types and leaves many other deviation types intact. This can, in favourable conditions, cause considerable errors in the analysis results. It is possible to estimate goodness of fitting visually, because if deviation types, which cannot be analysed, exist in a measurement a low-gradient difference should occur between fitted and real measurement curve. This verification of neglected deviation types can be automated for example in the following way: The difference between the analysed results and the real measurement data is first low-pass filtered and then the minimum and the maximum of the filtered difference are searched. The difference between found maximum and minimum is then compared to a total circularity value of a measurement and on this basis one can judge whether the analysis is good enough.

3.6.1.2 Recognition zones

The length of recognition zones affects the results. Long zones can cancel measurement data, which would have been needed for analysis. But also a short zone can leave bad transient points inside the analysis area and hereby cause bad results. Transient points can easily be observed visually in a measurement graph like too long zones, too. Differences in analysis results caused by different length of recognition are more difficult to find, because it is specific to a single measurement and changes in measurement graph are located in a short area and do not have any repetitive nature. This also quite severely prevents the automatic handling of this uncertainty source. It is possible to just have a limit for a maximum distance of a point to a fitted feature and if this limit is exceeded the system should announce a warning on a possible too short a recognition zone. Too long a distance would mean in this case that points from some other feature are included in the area of the current feature.

3.6.1.3 Singularity and rounding

Some errors in the analysis are caused by pure rounding errors in calculation. The method is based on matrix manipulations and big matrixes can sometimes behave badly, especially when they are close to a singular point. These singular points are also in otherwise bad for an overall performance of the method, because at those points it becomes very sensitive to a measurement uncertainty and other sources of uncertainty. Altogether it means bad behaving of the method if a matrix is close to a singular. In this case Singularity is caused by two (or more) deviation types, which are very similar in their behaviour. Therefore, the method carefully selects the deviation types to be included in the calculation and abandons some of them, if singularity is close. This causes shorthanded analysis, but the overall performance of the system for the included deviations is better. The restriction mentioned in 3.6.1.1 should be noticed here.

3.6.1.4 Ambiguous deviation types

If a single deviation type, which is analysed by the method, can be caused by multiple reasons in a real machine tool, the results can be misunderstood. Some not documented changes in a test accomplishment can also cause variation in results.

A good example of this is backlash, because it is caused by a real clearance in a ball screw and by elasticity in a drive system. This means that even if the backlash should

stay constant in different situations, it, indeed, varies depending on the feedrate, acceleration forces, material and temperature of a machine tool.
There is also reason to pay attention to different angular deviations, which are here explained only by a single deviation type, the lateral play, and, partly, by the backlash. However, there exist rolling, yawing, and pitching in all the axes of a machine. Thus just a small difference in the centre point of a measurement can cause significant changes in the value of the lateral play and backlash, if those angular errors are present. This ambiguousity is caused by the incapability of the measurement methods operating in one plane only. It is possible to analyse angular deviations in a plane in greater detail, but in such a case we easily face the singularity problems.

3.6.2 External uncertainty

3.6.2.1 Measuring device

A measuring device itself has some uncertainty, that can be either systematic or stochastic. Stochastic errors are not generally a big problem for an analysis method, because these deviations are filtered by the use of an average and least-squares fitting. But then again, systematic errors can cause significant differences in the analysis results, because those errors can just fit to look like some specific deviation type and thus the measuring device errors will be explained by the machine tool deviations in the analysing process. These types of errors can thus cause serious misinterpretations and they should be studied carefully. The temperature measurement and compensation are of great importance in this matter.

3.6.2.2 Measuring method

A measuring method involves some assumptions about the behaviour of a machine. A direct measurement does not produce any force against the cutting head and the inspected paths may not always be characteristic of the tasks executed by a machine. This causes dissimilar inspection results compared to a real situation, which, of course, is the target of our real interest.
A comparison between different measuring methods has to be carried out in order to solve which methods fit the current situation the best. It is possible that very different methods, for example a cross grid encoder and a test piece, give out similar results and thus both methods are known to be valid for the machine in question. Even if the results are not similar, it is possible that they have some correlation and can thus be used when this dependency is taken into account.

3.6.2.3 Local testing

Most quick test methods for measuring a machine tool are quite narrow-range. Measurement data can thus cover the machining space only partly and some areas are left beyond the measurement. It is possible to repeat measurements in several positions in a machine tool table, but this annuls the fastness and easiness of a method. That is why a single measurement is often used to stand for the whole plane, even if it can cover it only partially. This causes naturally distortion in the measurement analysis results and they can present well only the ability of the area really measured. However, it is possible in many cases to make the measurement in a way that one measurement only can present the whole plane of the machine well enough. Nevertheless, this restriction applies to all quick test measurements.

3.6.2.4 Temperature

Temperature is always an important factor in machining and measurements. It is mentioned to contribute more than 50% of the overall error [Weck et al. 1995]. This emphasises how concerned the user should be about this matter when performing the tests.

The test piece machining or a direct measuring of a machine tool has to be carried out in settled temperature which equals to normal operating conditions. It requires the warm-up of a machine tool and attention paid to possible outer disturbances, for example sunshine, an open street door and a heat source of other machines. From the point of view of this method, it is important to pursue conditions close to the ordinary situation, and not to get them better than the ones which real production undergoes. This concerns especially the temperature level, however temperature fluctuations have to be minimised.

When a test piece is measured by a CMM, it again requires paying careful attention to temperature. The user must comply with the general rule of measurements to let the piece to be measured thoroughly absorb the room temperature, to use right expansion coefficients and accurate temperature measurement.

Generally errors on the temperature level during machining or measuring and inaccuracy in expansion coefficients cause a false scaling factor result in the analysis. Fluctuation of temperature during machining or measuring increases uncertainty of all analysis results, because it causes an irregular deviation path, which cannot be well explained by any known deviation type.

3.6.2.5 Machining test specific

Material

Differences in material cause deviations in test results. Even if the last cut is thin, differences in machineability and forces arising from cutting cause deviation in pieces to some extent. Thus it is advisable to use always the same raw material when tests are repeated and also to use exactly the same material as for ordinary production pieces. This way a test piece will reflect the real situation of the production quality. The effects can be found by a CMM measurement and then corrected if necessary.

Machining parameters

The depth of the last cut inevitably has an influence on the final dimensions of a test piece. A mode for a corner approach, servo tuning parameters, approach directions in an NC-program and small fluctuations in the programmed feedrate have their impact, too.

The tightness of the fastening of a test piece in a fixture causes some changes in the dimensions of the raw material and thus later also in the final piece. The significance of this error source depends greatly on the used material and clamping mechanism.

Surface quality

When measuring a test piece in a CMM, surface quality causes deviations in results depending on the interval of measurement points and the diameter of a probe. Thus taking a greater amount of points with in a measurement can reduce the influence of bad surface quality.

Thin finishing cuts cause small forces and, accordingly, deflections are not big either because of the relative high stiffness of the machine tools. However, those finishing cuts produce forces with strong periodically variable components. The relationship between the variable force, variable deflections and their imprints on the machined surface is rather complex [Tlusty 1990].

Tool wear

A wrong preset value of a tool is to be taken into account in analysis as well as a possible slightly false touch probe diameter. But no attention is paid on the wear of a tool during machining. This inevitably causes some deviation in the results, but this amount will be indiscernible small, because only the wear during finishing can be observed.

CMM deviations

General concern on CMM measurement accuracy and uncertainty is naturally valid here. It concerns all the environmental aspects as well as good measuring practise. Systematic and random errors of a CMM affect in different ways the analysis results correspondingly causing systematic and random errors there.

Systematic CMM errors can even be seen directly in an analysis result. Especially when a test piece is measured exactly in the same order as it was manufactured, the same type of deviations in a machine tool and CMM are added to each other. The amount of a deviation in a CMM is subtracted from the value of a machine tool and this value is shown as the result of an analysis. This phenomenon occurs only when an error source in a CMM corresponds to a deviation type handled in an analysis, otherwise systematic error cause just random error of an analysis to increase.

Random errors of a CMM cause uncertainty of the results to increase. Random errors cannot cause any systematic error in the analysis results, but they correspondingly arise random errors in the analysis instead. Because analysis examines only low frequency deviations in a machine tool, the analysis is also more sensitive to low frequency random errors in a measurement, whereas high frequency errors have almost no influence at all.

3.6.3 Deviation in practical tests

Practical tests in various conditions are performed to determine uncertainty estimates for different deviation types. Because uncertainty consists of many elements, dedicated tests are performed to find out values for individual uncertainty sources. However, the tests can mainly reveal only the repeatability of a method, not absolute accuracy.

Since the sources of errors are so various, it is not necessary to try to determine all the independent sources. Instead, some typical test experiments are arranged to find out a combined variation of the method in current conditions. These experimentally achieved combined uncertainties can be used later to determine the total uncertainty of the method.

Single CMM repeatability

A CMM repeatability test uncovers a united uncertainty of singularity and rounding, surface quality and CMM random deviations. A single test piece is measured multiple times in this test. Then these measurements are analysed and the analysis results are compared with each other, from which a deviation is calculated.

Test piece repeatability

Many copies of test pieces are manufactured in a single machine tool in conditions as close to each other as possible. The pieces are measured with a CMM and analysed. This test puts together uncertainties of singularity and rounding, temperature, material, surface quality, clamping, tool wear and CMM random deviations.

Machining parameter influence

The test pieces are manufactured with different machining parameters, i.e. the depth of a finishing cut and the mode of corner approach, to determine their influence. The results achieved can be compared to the results obtained by a test piece repeatability experiment.

Cross-grid encoder repeatability

The same machine is measured repeatedly in the same position and plane with a cross-grid encoder. The results again are compared with each other. The variation observed is a combination of uncertainties arising because of singularity and rounding, temperature and measuring device.

4 EMPIRICAL PART

4.1 Validation software

A software program was developed to assist the validation of the presented method. The main frame and the user interface of the program were created by using Microsoft Visual Basic 5.0™. A calculation module was compiled into a dynamic link library (DLL) with Microsoft Visual C++ 5.0™.

4.1.1 Database structure and data flow

The analysis system involves information from three sources. Thus database is divided in three separate areas. It makes it possible to physically distribute data storage close to their native sources. Links to those sources are determined in the analysis program, which gathers this information together to form a meaningful way. Databases are in Microsoft Access 97™ format.

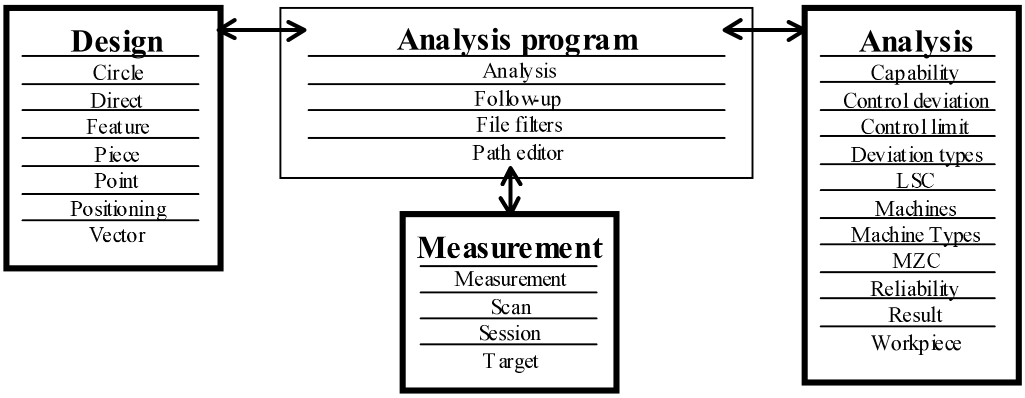


Figure 21. Databases in the analysis system

The design database includes information on dimensions of measured pieces. It has data both for real workpieces and test pieces as well as paths of direct measurements. The fields included in the data structure are presented in Table 2.

The measurement database stores data points from a measuring equipment. Data is not stored in the native format of a measuring device but in a generic format which is explained in chapter 3.4.4. Currently the analysis program handles preprocessing of raw measurement points, even though in some cases processing could be distributed into a separate program.

The analysed results of measurements are stored in analysis database. The results are used for the follow-up of individual machine tools, control limit monitoring and comparisons between measuring methods. This database is native for the analysis program and it uses this data storage also for internal settings and configurations.

4.1.2 Analysis program

The analysis program is capable of reading measurements, analysing them in the earlier presented way, storing results in a database and showing results in figures and graphs. It has own functions to read different file formats, to edit measuring paths and to follow-up magnitudes of deviations. A sample case of the usage of this software is given in appendix 13.

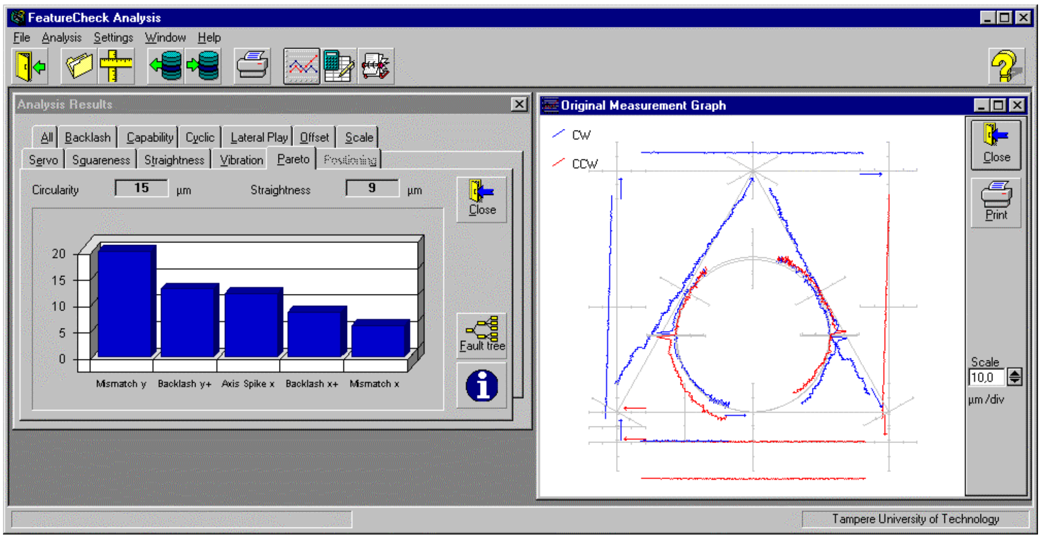


Figure 22. Analysis results in figures and in graph

Generic inner data format enables the use of both direct and indirect measurements. There are two phases where handling differs between these two methods: file input and existence of tool compensation.
Direct measurements have path information included in a measuring file and this data is used as it is. Indirect measurements, instead, require predefined information on target paths. The operator inputs this information using a simple 2-D path editor function.
Tool compensation is used for machined indirect tests. For each tool that is defined in a path an individual deviation in a tool radius is calculated using the method presented earlier. This calculation is disabled for direct measurements.

4.1.3 Long term follow-up of deviation magnitudes

The program gives an opportunity to follow-up magnitudes of either individual deviations or quality capability values. This is a straightforward query in a database to show a trend according to some classification keys. The trend is drawn in respect to time, and real figures are also shown in a table.
User defined control limits are combined to this function in order to give an alarm if one of the individual deviations rises above a certain limit. This check of warnings is run each time after analysis of a single measurement and at a start-up of the program.
All the measurements are included in this review and each equipment type is shown by its own colour. Thus comparison between measurement methods becomes applicable. It is possible to compare development of results in respect to time and with each other. Even though in most cases this is not absolutely necessary after first initial

tests, however, the possibility is sometimes welcome when unexpected behaviour occurs.
These simple tools are intended to ease the systematic monitoring of a machine tool condition. It forces the user to save data in the exact same format every time and it also stores vital information on time and conditions of the test.

4.2 Testing procedure

The analysis system has been tested with real machine tools and with simulations. Practical testing has been made with double ball bar, cross-grid encoder, test pieces and laser-interferometer. Comparison between methods and repeatability of results has been accomplished. An individual case is presented where analysis results are fully used to compensate a machine.

4.2.1 Simulations

Computer simulations were first used to evaluate functionality of both the algorithm itself and the programming. Simulation program produced measurement files, which were read by the analysis program. The results of analysis and initial values of simulation were then compared with each other.

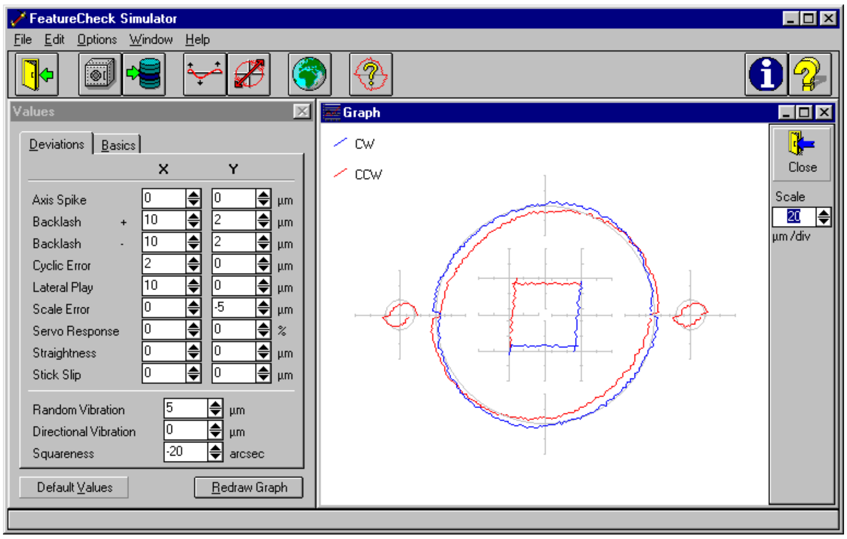


Figure 23. Initial values and produced graph in simulation

The simulation algorithm is a simple stepping engine. It first reads the target path data and based on this information it creates target points along the path with a predetermined step. It starts to step these target points and adds to them deviations which the user has given. This way it can take into account changes both in motion direction and feedrate.
Simulation is not used to evaluate superiority of analysis, but only to validate correctness of functions and logic in the analysis program. Because of the nature of the problem and the assumption of the simulation that no other deviation types, except the given ones exist in the measurement data, analysis results should agree with initial

values of the simulation in precision of computational accuracy. An example is given in appendix 13.

4.2.2 Primary practical tests

When simulations had given acceptable results, the analysis system was used together with a double ball bar and a cross-grid encoder to measure a simple xy-table. The table is equipped with a new Siemens 840D controller and therefore it is easy to implement artificial deviations in the machine. This was made by using compensation tables to create a known amount of squareness error, scale errors and backlash. The machine was measured again and the achieved results were compared to the original analysis result.

This testing method was used to ensure that assumptions made in simulation program and the analysis are valid with real machine tools. Because the used machine is not mechanically of a high level, repeatability in results was not expected to be especially good. However, this phase more or less is able to show, whether the results have the right magnitude, but it is not capable of indicating repeatability of the analysis system.

4.2.3 Repeatability

Measurement sets are repeated with the same machine tool in order to evaluate how well the measurement results repeat themselves. Each measurement method has its own kind of a repeatability for each deviation type and thus testing is made separately for double ball bar, cross-grid encoder and a co-ordinate measuring machine.

Test piece measurements are reproduced in four ways. First several test pieces are machined with the same machine tool and with the same settings. Secondly, the depth of the finishing cut is changed in order to change the cutting force, which is an unknown parameter in the analysis. Thirdly, CMM measurement is repeated with a single test piece. Fourthly, the same test pieces are measured with two different co-ordinate measuring machines, one of them representing a high accuracy measuring machine and the other one being a standard CMM.

4.2.4 Thermal behaviour

While thermal behaviour is the most important single source of errors of machine tools, its effect must be studied even if the presented method doesn’t handle thermal errors. All the other tests explained here are carried out in machines, which have been warmed-up.

There has been carried out a test procedure during which a machine tool is measured continuously with a double ball bar. At the start of the test the machine tool is in a cold state and during the test it is brought to the warmed-up state. Its temperatures are recorded during, before, and after the testing.

4.2.5 Comparison

A few machine tools are measured with a laser-interferometer, a double ball bar, a cross-grid encoder and by machining a test piece. The results achieved from each method are compared with each other. The double ball bar is selected to be the basic system of the measurement, because it is proven to be a reliable method [Oksanen

1996] and because it gives the opportunity to analyse almost all the deviation types [Kakino 1993], which the new presented method can also reveal.
Comparisons between methods offer real, absolute information on the accuracy of the results. When this kind of hard proof is required, the reference method has to be both well established and standardised. This prerequisite narrows absolute comparisons to include backlash, scale error and squareness only. On the other hand comparisons can also reveal differences between measurement methods. This latter comparison type can comprise all the deviation types, which are handled in the current analysis method.
Laser-interferometer measurements are interpreted according to the ISO 230-2 standard. Positioning errors and backlash values are compared to equivalent values, achieved of cross-grid encoder and test piece measurements.
Double ball bar measurements are analysed using the software supplied by Renishaw plc, and measurement installation for DBB is setup according to ISO 230-4 standard. Double ball bar device, method and its reliability have already been studied rather thoroughly [Bryan 1982] [Kakino et al. 1993] [Oksanen 1996]. Oksanen presents results which show that backlash, squareness and scale mismatch agree well with laser-interferometer and with square normal measurements. Comparison between the analysis results achieved from Renishaw analysis program (Renishaw Ballbar Data Analysis 4.21) and the method presented in this work are also presented.
Important comparison is concluded between the test piece and cross grid encoder measurements. They can both reveal similar deviation types in a machine tool, but the conditions and complicity of the measurement process differ significantly from each other [see chapter 3.6.2]. The test piece used in this comparison is described in chapter 4.2.8.

4.2.6 Compensation

When parametric deviations, based on measurement and analysis, have been found, these values are used to compensate the machine tool. Compensation tables are built on information of analysis, and servo gain is also tuned on the basis of the results.
Geometric deviations compensated with tables, can be activated by a single run. As again the servo tuning needs iterations, because the values, achieved from the analysis, tell only the direction of change, not the amount of change.
It is common in research reports to use really old and bad behaving machines in order to demonstrate functionality of compensations. This will be the case here, too. Industrial companies are not willing to tune their machines if not really necessary especially if some risks exist. Smooth functionality of a compensation scheme must be at first shown before the industry is willing to experiment new approaches. On the other hand it is natural that when geometrical errors are small, thermal behaviour dominates and thus there is no interest to remedy just one part of the problem.

4.2.7 Cross grid encoder test path

The cross grid encoder and the analysis method enable the use of free test path forms. However, some rules have been applied to the testing of the method in order to unify the results. The path used has similar forms with the test piece so that the analysis can also find similar deviation types in the test.
The whole path is driven, using the same feedrate, but multiple tests can be performed with other feedrate settings. All the machine tools are measured at least with 400

$^{mm}/_{min}$ and 2000 $^{mm}/_{min}$ feedrates when some tests are done also with 10000$^{mm}/_{min}$. Similar test path is used for all three planes.

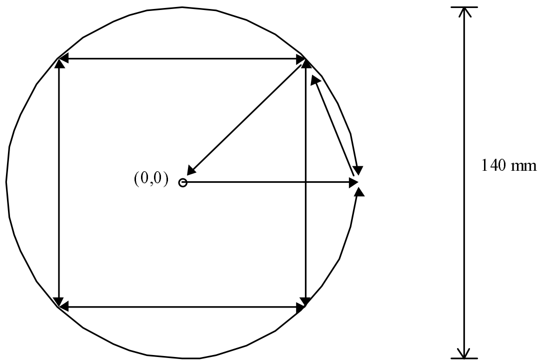


Figure 24. Typical cross grid encoder test path

4.2.8 Test piece

An own test piece was designed and used in both repeatability tests and in comparison. This was done, because the standardised test pieces do not have sufficiently rich features to reveal all of the deviations the analysis system handles. The main difference is that this new piece has a well defined inner machining [Table 3].

Simpler test pieces were used at first, but unfortunately the results did not indicate good behaviour. The first problem arises because of tool compensation. If a test piece includes only external machining and if these machined surfaces lie relatively close to each other in the direction of one axis, the distinguishing of scale errors from a tool compensation error is difficult. That means in the matrix notation, which is used in this work, that matrix *A* [Formula 1] approaches to a singularity point. And furthermore this causes large deviations in results.

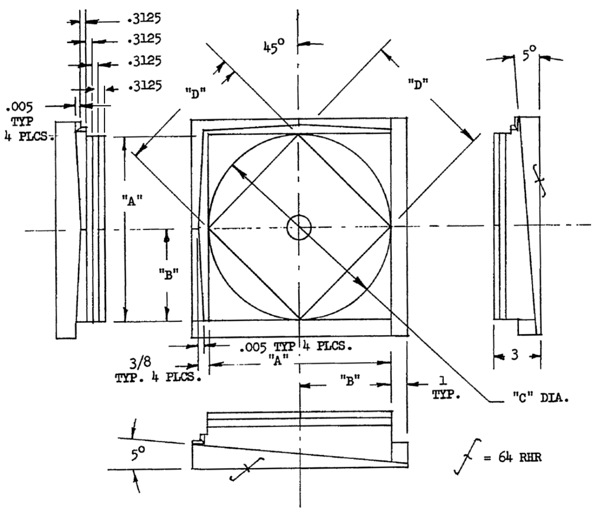


Figure 25. NAS 979 test piece [NAS 979]

NAS 979 test piece [Figure 25] offers a good selection of features. There is circular and linear interpolation. Circular and linear interpolations are, however, instructed to be made in one direction only, but this drawback can easily be revised just by adding one more level to both surfaces, which would be machined in reverse direction. Linear interpolations are also at an angle of 45 degrees which offer a good indication of the behaviour of a machine in interpolation. This NAS piece is clearly better for the purpose of this work than the ISO 3070 test piece [Figure 25], because NAS has also linear interpolations.

A test piece presented in ISO 10791-7 offers equal features as the NAS piece from the point of view of the analysis method in use. However, the test piece can flexibly be used to discover errors of rotary axes as well [Knapp 1997].

However, an own test piece was developed for this study. This was done in order to get well defined inner machining and a straight angle linear interpolation. Straight angle linear interpolation was used to get assured estimates for squareness. This way straight lines should not suffer at all of an incomplete servo tuning. Inner circles are machined by up- and down milling. Thus they offer an indication of a deflection to the direction of both axes, not just one axis as the groove in the NAS piece. Outer circles are machined in two directions (up- and down milling) as well. Edges of the piece are machined with linear interpolation both in up and down milling directions.

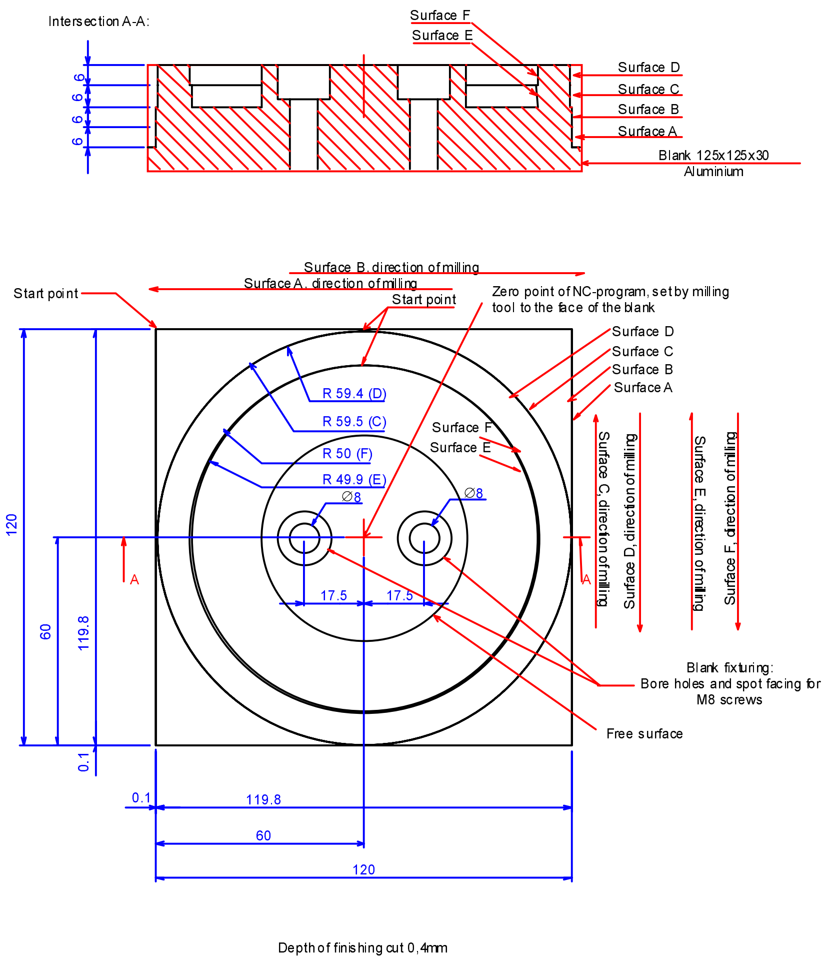


Figure 26. A test piece used in the study

Table 3. Comparison between NAS 979 and own test piece

Feature element	NAS 979	Own piece
Circular interpolation CCW with up milling	●	●
Circular interpolation CCW with down milling	○	●
Circular interpolation CW with up milling	○	●
Circular interpolation CW with down milling	⊙	●
Linear interpolation along 1st axis with up milling	●	●
Linear interpolation along 1st axis with down milling	○	●
Linear interpolation along 2nd axis with up milling	●	●
Linear interpolation along 2nd axis with down milling	○	●
Diagonal interpolation with up milling	●	○
Diagonal interpolation with down milling	⊙	○

● = The piece contains the feature.
⊙ = The piece can contain the feature with minor modifications.
○ = The piece does not contain the feature.

The pieces were machined of aluminium (ALSI1MGT6), and a single end mill tool was used to mill all the forms. In this case it is preferable to use just one tool, because that way the tool related errors are being reduced. A coolant was used during machining. A blank was fixed with two M8 screws to prevent major deformations in a piece. The same holes were used in CMM measurements also to fix pieces on the measurement table.
The size of a piece could naturally be scaled, but here all the pieces are of the same size: 120mm x 120mm. The same size of pieces speeds up CMM measurements, allowing the use of a single measuring program and fixtures.

4.3 Results

4.3.1 Simulations and primary practical tests

Simulation tests were run to validate that algorithms in the analysis software correspond to a theoretical model. Only the deviation types introduced in chapter 3.5.1, were used in the simulation. Thus the results, achieved with the analysis, agree comprehensively with initial values given to the simulation.
Primary tests, performed in the xy-table, were capable of showing results indicating an acceptable level of behaviour for the system. The test machine had trapezoid lead screws without automated lubrication and this, together with worn slides made the behaviour of the machine change continuously. Thus the machine would give significantly different values for backlash in the morning with both well lubricated slides and lead screws, compared to the afternoon, when it was already running dry.
A short test was also performed with a highly accurate milling machine, using a cross-grid encoder and two different measurement paths [Hölsä 1997b p.522]. This test was interpreted to give acceptable results considering the size of the test path [Table 4]. The first test path was a circular test with CW and CCW directions and the second path was a triangle. Thus it was not even possible to get results for all deviation types, but the results of backlash, scale error and squareness are comparable.

Table 4. Primary test results [Hölsä 1997b p.522]

Deviation type	Circles		Triangle	
	x-axis	y-axis	x-axis	y-axis
Capability	circularity: 21 µm		straightness: 3 µm	
Axis spike	5 µm	9 µm	-	-
Backlash	1 µm	1 µm	1 µm	0 µm
Cyclic error	0 µm	0 µm	-	-
Lateral play	0 µm	1 µm	-	0 µm
Scale error	33 µm/m	-8µm/m	40 µm/m	-16 µm/m
Servo mismatch	-0,7 µm		-	
Squareness	-44 µm/m		-83 µm/m	
Straightness	0 µm	0 µm	0 µm	0 µm

4.3.2 Repeatability

The statistics of repeatability tests are carried out in a way that individual results are compared with the common average of each set in the comparison. Uncertainties are shown with the coverage factor 2. Results of the first axis and the second axis as well as all backlash values are combined together in order to make the reading of the results easier.

4.3.2.1 Repeatability of cross grid encoder measurements

Cross grid encoder measurements were repeated with the same machine tool twice in all three planes with two different feedrates. Time between measurements is approximately two hours, but they are measured with newly setup measurement installations. In each case the achieved analysis results are compared with each other. The differences are collected together and the deviation values for each deviation type are calculated. Calculations are presented in appendix 2. The following results were achieved:

Table 5. Repeatability in cross grid encoder measurements

Deviation type	Uncertainty (2s)	Unit
Squareness	0,70	arcsec
Scale mismatch	1,5	µm/m
Scale error	3,0	µm/m
Backlash	0,39	µm
Straightness	1,6	µm/m
Servo mismatch	0,023	µm/max(feed [mm/s])
Servo lag	0,069	µm/max($feed^2$/radius)
Cyclic error	0,23	µm
Axis spike	0,57	µm
Lateral play	0,10	µm
Random error	0,11	µm

4.3.2.2 Repeatability of co-ordinate measuring machine measurements

A measurement of a single test piece was repeated seven times with the same co-ordinate measuring machine. Four of those measurements were done just after each other, i.e. with an interval of three hours. Three last ones were repeated similarly after four days. Measurements were divided this way for practical reasons and to simulate a typical arrangement in workshops. The measurements are completed during one week, which can be regarded as a maximum time for a test piece to wait for a co-ordinate measurement. In both measurement sets the piece has been placed and oriented similarly. This machine, used in measurements, Sip CMM5, represents a high accuracy device of its own class. Calculations are presented in appendix 4.

Table 6. Short term repeatability in high grade CMM measurements

Deviation type	Uncertainty (2s)	Unit
Squareness	0,46	arcsec
Scale mismatch	9,3	µm/m
Scale error	12	µm/m
Backlash	1,6	µm
Straightness	2,6	µm/m
Servo mismatch	0,034	µm/max(feed [mm/s])
Servo lag	0,032	µm/max(feed^2/radius)
Cyclic error	1,7	µm
Axis spike	0,94	µm
Lateral play	0,090	µm
Random error	0,42	µm
Tool compensation	0,20	µm

Using the exactly same CMM, measurements were repeated after five months. Three different test pieces were measured and their results were compared to the earlier analysis results. Calculations are presented in appendix 4.

Table 7. Long term repeatability in high grade CMM measurements

Deviation type	Uncertainty (2s)	Unit
Squareness	4,1	arcsec
Scale mismatch	36	µm/m
Scale error	29	µm/m
Backlash	1,7	µm
Straightness	5,8	µm/m
Servo mismatch	0,12	µm/max(feed [mm/s])
Servo lag	1,1	µm/max(feed^2/radius)
Cyclic error	0,53	µm
Axis spike	1,4	µm
Lateral play	0,77	µm
Random error	0,18	µm
Tool compensation	0,44	µm

Another co-ordinate measuring machine, Zeiss UMC850S, was used to measure one of the test pieces to determine its repeatability compared to the high grade CMM.

Zeiss UMC850S represents standard level of a CMM, which is widely available in industrial companies. Five measurements were completed using the same measurement installation. These measurements were repeated consecutively and should thus be compared to short term repeatability results of a high grade CMM [Table 6]. Calculations are presented in appendix 4.

Table 8. Short term repeatability in standard grade CMM measurements

Deviation type	Uncertainty (2s)	Unit
Squareness	0,34	arcsec
Scale mismatch	14	µm/m
Scale error	16	µm/m
Backlash	1,7	µm
Straightness	1,6	µm/m
Servo mismatch	0,054	µm/max(feed [mm/s])
Servo lag	0,046	µm/max(feed^2/radius)
Cyclic error	0,49	µm
Axis spike	1,4	µm
Lateral play	0,38	µm
Random error	0,26	µm
Tool compensation	0,45	µm

4.3.2.3 Repeatability of test pieces

Multiple copies of similar kinds of test pieces were manufactured by two different machine tools in order to compare results between the pieces. Conditions during the machining were kept similar between the pieces in a way it is possible in ordinary machine shops. Thus the following factors were kept the same in all pieces: tool, fixture, material and NC-program. Machine tools did not have a temperature control, but a warming cycle was used before the machining of the first piece and the subsequent pieces were machined just after each other.

Table 9. Test piece repeatability in high grade CMM measurements

Deviation type	Uncertainty (2s)	Unit
Squareness	9,1	arcsec
Scale mismatch	69	µm/m
Scale error	59	µm/m
Backlash	4,0	µm
Straightness	13	µm/m
Servo mismatch	0,64	µm/max(feed [mm/s])
Servo lag	2,8	µm/max(feed^2/radius)
Cyclic error	2,0	µm
Axis spike	2,0	µm
Lateral play	4,3	µm
Random error	0,68	µm
Tool compensation	4,6	µm

Two different feedrates were used in both machine tools, but comparisons were completed between similar pieces using the same CMM. Calculations are presented in appendix 3.

4.3.3 Thermal behaviour

The behaviour of a single machine tool is studied during its warm-up period. A double ball bar is used in this case to measure the machine tool because of its short measurement cycle. The achieved measurement results are analysed by the method presented in this work

The temperature values of servomotors, scales, ballscrew nuts, machine body and room temperature are recorded during measurements. Pt-100 thermal resistors and HP-data logger is used to follow the state of those elements. The duration of the test is four hours and totally 69 individual measurement runs are completed during that time. Because the strongest increase in temperature is observed in the y-axis servomotor, this temperature is used when studying temperature dependency of individual deviation types.

The achieved results are presented in detail by graphs in appendix 5. Linear dependency between the temperature and the amount of deviation is calculated for each deviation type. There is a significant relation found in the scale mismatch and the scale error when other deviation types do not indicate sensitivity to temperature changes. The expansion rate on the x-axis is found to be in this case 1,4ppm and on the y-axis 4,2ppm per degree centigrade.

Thermal sensitivity of the scale error plays a significant role also in latter studies between different methods. This phenomenon is clearly identified to be the most important single error cause of machine tools by many researchers [chapter 2.2] and thus there seems to be no reason to despite it, when using this new method, either.

4.3.4 Comparison

The comparison between different methods is presented in terms of bias and uncertainty. Bias shows average difference between methods and thus indicates whether a systematic trend exists between methods. The uncertainty value is a range where results should fall into a relation with the basic analysis method. This uncertainty is given assuming normal distribution of difference and 95% certainty level. Thus the significant value is the uncertainty, the bias value is just a tool for the development of the method.

4.3.4.1 Difference to native DBB analysis method

Exactly the same data files were analysed by the method presented here and with the analysis program supplied by Renishaw plc. The given results were subtracted from each other and two characteristics were calculated for each deviation type.

Average difference reveals a bias between methods. Uncertainty value gives a range where results of the new method would fall compared to the native DBB analysis in a case where difference between methods would be normally distributed.

Table 10. Difference between native and new analysis method in DBB measurements

Deviation type	Bias	Uncertainty	Unit
Squareness	-0,02	0,08	arcsec
Scale mismatch	-2,3	5,1	µm/m
Scale error	0,77	3,3	µm/m
Backlash	-0,05	1,8	µm
Straightness	-0,61	2,4	µm/m
Servo mismatch	-0,03	0,08	µm/max(feed [mm/s])
Servo lag	-	-	µm/max(feed^2/radius)
Cyclic error	-0,23	0,71	µm
Axis spike	1,1	4,0	µm
Lateral play	-0,06	0,28	µm
Random error	-	-	µm
Tool compensation	-	-	µm

Thus the most significant differences can be found in a scale mismatch and in an axis spike. The analysis results differ from each other, but on the given accuracy of the measurement device and even in relation to the needed accuracy in a machine tool inspection these differences alone would not be crucial.
All the measurement sets in this comparison are taken from a single machine tool measurement session, which includes altogether six measurements having different plane and feedrate combinations. A detailed summary of results is presented in appendix 6.

4.3.4.2 Difference between cross grid encoder and DBB

Measurements were collected from six different machine tools [appendix 12] in order to compare double ball bar and cross grid encoder measurements with each other. All three planes were measured in every machine using two different feedrates. One machine was measured twice and thus the total number of measurements were 42.

Table 11. Difference between DBB and cross grid encoder measurements

Deviation type	Bias	Uncertainty	Unit
Squareness	-1,4	9,6	arcsec
Scale mismatch	3,8	130	µm/m
Scale error	79	200	µm/m
Backlash	-1,1	6,2	µm
Straightness	-4,9	120	µm/m
Servo mismatch	0,02	0,58	µm/max(feed [mm/s])
Servo lag	-	-	µm/max(feed^2/radius)
Cyclic error	0,06	2,5	µm
Axis spike	4,1	11	µm
Lateral play	0,11	1,7	µm
Random error	-	-	µm
Tool compensation	-	-	µm

Some of the measurements include clear anomalies from the modelling principles used in the analysis and thus differences between methods also reach rather high values. These cases are, however, included in the comparison, because this would also be the case in every day inspections. One sample case is the measurement pair having IDs 95 and 96, which have suffered from a loose spindle locking during the measurement. Therefore, achieved values should reliably describe the difference between DBB and cross grid encoder measurements when analysed by the proposed method.

Here the most significant differences between the methods can be found in scale mismatch, scale error, straightness, and axis spike. Also difference in squareness is considerable, because this deviation was expected to be reliable in the analysis. Altogether differences are larger than can be accepted. However, differences between machine tools are big [see appendix 7 and 11] and this fact brings up some observations.

The new analysis system behaves badly when repeatability of the machine tool is bad. It cannot explain deviations correctly and repeats badly between measurements. This is rather natural considering the limited collection of deviations it has to use.

One comparison case is shown in Table 12. Results of DBB and cross grid encoder measurements in xy-plane with both 400 $^{mm}/_{min}$ and 2000 $^{mm}/_{min}$ feedrates are compared to each other. Generally results are consistent, but differences in scale mismatch and scale error are large. Thus this individual case agrees well with the general results shown in Table 11.

Table 12. Comparison case between DBB and cross grid encoder in xy-plane

Measurement:	2000 $^{mm}/_{min}$ ID: 86			400 $^{mm}/_{min}$ ID: 85			
	DBB	Grid	Difference	DBB	Grid	Difference	Unit
Squareness	-17,68	-16,8	0,9	-17,4	-17,8	-0,3	arcsec
Scale mismatch	40,6	-16,3	-56,9	44,1	-1,5	-45,6	µm/m
Scale error x	-11,8	51,5	63,3	9,7	47,1	37,4	µm/m
Scale error y	-52,4	67,8	120,2	-34,4	48,5	82,9	µm/m
Backlash x+	1,6	3,8	2,2	1,9	3,4	1,5	µm
Backlash y+	10,5	13,8	3,3	9,9	11,3	1,4	µm
Backlash x-	2,8	4,3	1,5	2,5	3,8	1,3	µm
Backlash y-	13,1	13,1	-0,0	12,5	8,7	-3,8	µm
Straightness x	4,3	5,1	0,7	8,3	12,4	4,0	µm/m
Straightness y	-2,7	1,3	4,0	-1,0	3,2	4,2	µm/m
Servo mismatch	0,0	0,1	0,1	0,1	0,9	0,7	µm/max(feed [mm/s])
Servo lag	-	0,7	-	-	6,2	-	µm/max(feed^2/radius)
Cyclic error x	1,0	0,8	-0,2	0,9	0,6	-0,3	µm
Cyclic error y	1,7	2,0	0,3	1,5	0,8	-0,7	µm
Axis spike x	7,7	14,3	6,7	0,0	0,1	0,1	µm
Axis spike y	3,7	10,1	6,4	0,7	3,7	3,0	µm
Lateral play x	-0,2	-0,2	-0,0	-0,1	-0,1	-0,1	µm
Lateral play y	6,8	5,9	-0,9	7,6	6,7	-0,9	µm
Random error	-	0,2	-	-	0,2	-	µm
Tool compensation	-	-	-	-	-	-	µm

Both cross grid encoder and DBB measurements are local and thus in machine tools where deviation values change quickly in a space also the analysis results easily vary considerably. All the measurements were not performed exactly in the same point of machining space for practical reasons and the measurement diameter of cross grid encoder is just 140 millimetres when DBB can easily cover 300 millimetres, which were generally used diameters in the tests.

4.3.4.3 Difference between the test piece and DBB

The test piece results, measured in a high-grade co-ordinate measuring machine, were compared to equivalent double ball bar measurements. Because of the nature of the tests these could not have been repeated just after each other and thus the thermal status of the machines has differed between the tests. Likewise changes in the CMM are present in these results.

The comparison was run on four different machine tools making altogether 16 test pairs. One of the machine tools had only one piece in comparison as the rest of them had three or more test pieces. The comparison was conducted in xy-plane only because of the mechanical structure of machine tools in the scope.

More detailed values are presented in appendix 8. Because of the large variation of the test pieces, a single test piece of each machine tool was selected to present the whole set. The piece case was selected from the middle or end of the machining so that the machine would have reached thermal equilibrium. On one of the machines there was only one test piece machined, and thus that single piece had to be used in this comparison.

Table 13. Difference between DBB and test piece measurements

Deviation type	Bias	Uncertainty	Unit
Squareness	1,7	10	arcsec
Scale mismatch	-2,4	72	µm/m
Scale error	76	170	µm/m
Backlash	-1,9	8,5	µm
Straightness	-4,2	23	µm/m
Servo mismatch	-0,24	1,18	µm/max(feed [mm/s])
Servo lag	-	-	µm/max($feed^2$/radius)
Cyclic error	0,29	1,5	µm
Axis spike	4,0	9,0	µm
Lateral play	-0,23	7,9	µm
Random error	-	-	µm
Tool compensation	-	-	µm

Differences between these two measurement methods are generally rather large, though differences in behaviour between the machine tools can be found. Especially differences in scale errors are so large that they cannot be accepted. Otherwise results show consistent trend even if the achieved uncertainty values are high. This becomes evident when looking at the comparisons of individual machine tool results in appendix 11. Some machine tools hold so large deviations that even though the results are in the same range, difference between them raises the average value shown above.

4.3.4.4 Difference between the test piece and the cross grid encoder

Individual cross grid encoder measurements were compared to the average of corresponding test piece measurement results. Because the form of the test pieces and the path of the cross grid encoder have similar elements, results are expected to correspond to each other better than DBB and CMM measurement pairs.

Table 14. Difference between test piece and cross grid encoder measurements

Deviation type	Bias	Uncertainty	Unit
Squareness	1,5	11	arcsec
Scale mismatch	42	110	µm/m
Scale error	0,58	96	µm/m
Backlash	-0,99	7,3	µm
Straightness	0,04	19	µm/m
Servo mismatch	-0,48	1,45	µm/max(feed [mm/s])
Servo lag	0,36	3,86	µm/max(feed^2/radius)
Cyclic error	0,36	2,0	µm
Axis spike	3,0	8,1	µm
Lateral play	-0,42	9,4	µm
Random error	3,1	6,4	µm
Tool compensation	-	-	µm

The test pieces to be included in the comparison were selected similarly to the comparison between DBB results. The grounds for the election are the same as well.

Contrary to expectation results are not better than compared to DBB. Achieved differences are about at the same level. Squareness error has a significantly large deviation even though similar kind of test paths should now give parallel results. Detailed values are presented in appendix 9.

One comparison case between cross grid encoder measurement and test piece measurement is shown in Table 15. The case here is measured in xy-plane and it has been accomplished with the feedrate of $400^{mm}/_{min}$. The results are not consistent for scale mismatch, scale error and straightness, but the results for other deviation types are closer to each other.

Table 15. Comparison case between cross grid encoder and test piece in xy-plane

Measurement	ID: 146 Grid	ID: 158 CMM	Difference	Unit
Squareness	-10,9	-11,7	-0,8	arcsec
Scale mismatch	10,0	54,5	44,5	µm/m
Scale error x	76,7	34,0	-42,7	µm/m
Scale error y	66,6	-20,5	-87,1	µm/m
Backlash x+	-7,0	-12,0	-5,0	µm
Backlash y+	-1,4	-6,1	-4,7	µm
Backlash x-	-8,5	-12,5	-4,0	µm
Backlash y-	1,0	1,8	0,7	µm
Straightness x	4,3	-0,7	-5,0	µm/m
Straightness y	-3,8	-4,1	-0,3	µm/m
Servo mismatch	-0,3	-0,9	-0,6	µm/max(feed [mm/s])
Servo lag	2,3	-0,5	-2,8	µm/max(feed^2/radius)
Cyclic error x	1,4	1,1	-0,3	µm
Cyclic error y	0,3	1,0	0,7	µm
Axis spike x	3,4	5,5	2,1	µm
Axis spike y	2,2	7,8	5,6	µm
Lateral play x	-1,1	-0,8	0,3	µm
Lateral play y	6,3	6,3	-0,0	µm
Random error	3,3	6,7	3,4	µm
Tool compensation	-	12,2	-	µm
Up milling deflection	-	-4,9	-	µm

4.3.5 Compensation

Compensation case [appendix 10] was completed on a simple two-axis table, which was controlled by the Siemens 840D numerical controller. The new controller offered all the possibilities to compensate the machine, but the old mechanical construction, on the other hand, caused enough deviations to correct. At the start the table was measured by a double ball bar and then analysed by the new method. Achieved results were translated to compensation tables [chapter 2.4.2.1] and fed into the controller.
The second checking of the achieved results were measured by a cross grid encoder. Because the results still showed some potential for further enhancement, new analysis values were used to adjust compensation tables. Third measurement run revealed circularity value of 19µm, which is one seventh part of the original 137 µm.
Even if the machine concerned does not well represent the real state of machine tools in every day use, it can still show the capability of a compensation scheme. It has the axes involved and the basic phenomenon behind is rather simple. This test cannot, however, show how a machine tool would act under a work load when heavily compensated or its influence on the surface quality.

5 DISCUSSION

The key topics in the discussion part are the differences found between the different measurement methods. The assumption has been that similar results can be achieved with different measuring methods, but experiments have shown that generally this is not true.
At first, the difference between the motion modes of machine tools is being discussed. This is a rather important issue while it involves an assumption that the deviation types used in this work are not universal, i.e. they would be variables of some third motion variables like feed acceleration, cutting force etc. It is inevitable that machines behave differently depending on the current motion style, but its significance to the magnitude of the used deviation types is an interesting question.
Because the model seems to work better on some machines than in some others, the reasons for this are also being searched. Six separate machining centres were measured during the study and they disclose some regularity in the performance of the analysis method.

5.1 Static and dynamic measurements

Traditionally machine tools are measured in a way that the movement is stopped at a measuring point. But in double ball bar, cross grid encoder and test piece measurements the machine is moving all the time. This seems to give some influence in the measuring results as well.
Thus, the reason for different results is not in the measuring device, but in the machine tool itself. It moves differently and the measuring device senses this motion. The error is made in the interpretation, when these two different deviations are put together. Indeed, the question is about two (or more) different parameters for a single deviation type depending on the used feedrate.
Generally this is an accepted truth for backlash. The GE Fanuc 16 controller, for example, has separate compensation values for cutting and rapid feedrates. The reason for this is the individual behaviour depending on the feedrate. Because the measurement of position accuracy according to ISO230-2 is performed by stopping the motion to take the measurement point, the achieved results inevitably differ compared to dynamic measurements. The same phenomenon is found in some earlier studies, too [Spaan 1995][Oksanen 1996].

5.2 Motion friction and interpolation

A machine tool is assumed to move smoothly during the measuring. Thus it is possible to determine which side loose motion deviations affect. However this assumption depends now greatly on the dynamic behaviour of the machine tool and also on the NC-program.
The motion mode setting has an influence on how the machine tool acts in corners. In the continuous cutting mode (G64) it moves smoothly, but it does not reach the exact corner point. Exact stop (G61) motion mode guarantees that the corner point is reached, but now motion of axes is not as smooth anymore. Anyway the exact stop

setting has been used to ensure good behaviour for the feature recognition. Round corners would spoil the analysis data badly. Figure 27 shows graphically difference between these two modes.

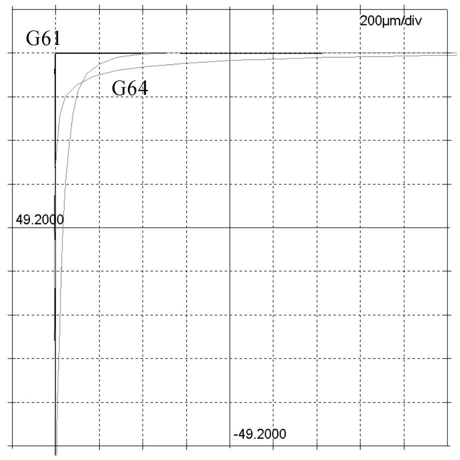


Figure 27. Motion path in corner with G61 (black) and G64 (grey)

Machine tools behave individually in cornering. Deceleration of motion of two different machine tools is shown in Figure 28. On the y-axis the x-position is presented and on x-axis the corresponding time. Both machines are run with the feedrate of $2000^{mm}/_{min}$ and exact stop mode active. Significant in the graph is waviness of the motion of the second machine compared to the first one.

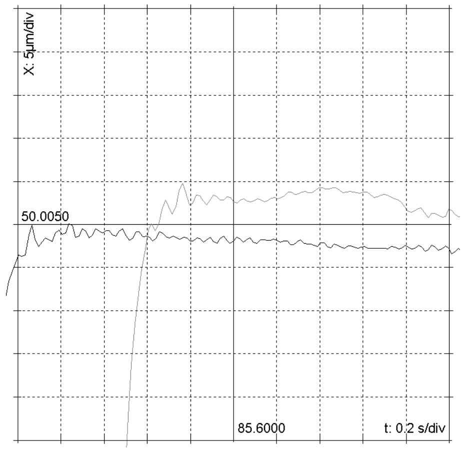


Figure 28. Deceleration of motion in two different machine tools

Such a behaviour alone is not a difficulty for the analysis method. But if it causes clearances to drift in an unknown position, it is impossible for the analysis method to determine the magnitude of backlash and lateral play. Furthermore, this prevents the other deviation values to get reliable estimates as well.

Even if similar NC-program was used to machine test pieces with those machine tools spoken above, the behaviour in machining is evidently different. This concerns approach directions. Thus the modelled path in the test piece evaluation for the second machine had approach directions opposite to programmed directions in vector features [see Figure 24]. Normally part description should reflect the actual machining path. This revised approach gave clearly better results and also results which correspond to

other methods. It seems, based on these experiments, that this machine tool pushes clearances in a deceleration phase to the other end than originally expected. For all the other machine tools expected behaviour gave better results and was used for comparison etc.
It should be noted here that this exceptional machine tool was not old nor in bad condition. Instead it was almost a brand new machining centre, which can be assumed to be rather common in industrial companies nowadays.

5.3 Erroneous assumptions in the model

The current analysis model can have faults on four levels: errors in deviation prototypes, missing of essential deviation types, wrong fitting procedure, and the negligence of six degree deviations. Any of these alone can cause severe errors in results.
The model operates solely in two dimensional space, leaving time dependent and the effect of the other axes untouched. Severe angular errors are handled by a simple deviation type of lateral play. This can interpret clearance in roll motion and in some cases also in yaw. Pitch of an axis is left to be combined with backlash. This method doesn't offer a tool to separate the pitch of an axis from backlash of the same axis. Likewise many other errors in six-dimensional space are left neglected. This should not, however, be a crucial disregard, since only two of the machine tool axes are moving during the test procedure. Thus it is justifiable to examine also only two axes at a time in the analysis. The test is then repeated in three planes so that all the axes can be covered.
Least squares fitting procedure was selected in chapter 3.3 to calculate deviation values. Related to this is the superimposing principle, used in the modelling i.e. deviation types are simply added to each other. Superimposing is, however, a widely accepted method [Ferreira&Liu 1993] [Kakino et al 1993] [Mou et al 1995] and it has also clear geometrical justification. Deviations at the end of the motion arms are so small that they do not have any real significance for the place of motional elements so that it would change the behaviour of some other deviation. Thus correlation between deviation types can be neglected, which naturally simplifies the problem significantly. Least-squares evaluation, on the other hand, is a robust method even if it cannot generally give the best result. The Chebyshev norm [Tajbakhsh et al. 1997] inevitably gives better results in theory and in ideal conditions. Based on the experiments, carried out in this study, those ideal conditions would hardly ever come true in real industrial measuring cases.
Missing some deviation type prototypes is rather probable. The question is: when are those missing types significant and when can they be neglected. An example case is shown below. A CMM measurement is analysed with and without estimation of up milling deflection.

Table 16. Influence of the estimation of up milling deflection (data set ID 126)

Device	DBB	CMM with up milling	CMM without up milling	Unit
Squareness	1,34	5,08	5,00	arcsec
Scale mismatch	-3,40	15,63	14,09	µm/m
Scale error x	14,30	38,90	38,12	µm/m
Scale error y	17,70	23,27	24,03	µm/m
Backlash + x	3,90	-2,05	-2,27	µm
Backlash + y	1,60	0,96	1,65	µm
Backlash – x	2,00	-0,18	-0,87	µm
Backlash – y	2,10	3,11	3,33	µm
Straightness x	1,30	-10,7	-10,87	µm/m
Straightness y	5,00	8,16	8,13	µm/m
Servo mismatch	0,06	-0,73	-0,84	µm/max(feed [mm/s])
Servo lag		0,79	0,79	µm/max($feed^2$/radius)
Cyclic error x	0,80	1,10	1,15	µm
Cyclic error y	1,10	0,77	0,74	µm
Axis spike x		2,89	3,25	µm
Axis spike y		7,89	7,83	µm
Lateral play x	**-2,35**	**0,41**	**5,74**	**µm**
Lateral play y	**1,00**	**1,33**	**-3,99**	**µm**
Tool compensation		30,08	30,08	µm
Random error		5,33	2,13	µm
Up milling		**-6,14**		**µm**

It is clear that missing estimation of up milling deflection causes lateral play to take place to explain the deviation observed in the measurement data. When up milling is included lateral play values come much closer to equivalent values, achieved in DBB measurement. However, it has also some influence on other deviation types and this influence is not only positive. This is a rather typical case. When a new deviation type is included in the analysis, some particular deviation types behave better, but general behaviour suffers. This is caused by the fact that the prototype matrix converge closer to singularity and thus uncertainty values for each deviation type rise. The case in question here is especially difficult, because lateral play and up milling deflection resemble each other so much.

Deviation prototypes are really simple equations presented in chapter 3.5.1. It is still possible to have errors in them, though it is highly unlikely. Still the behaviour like explained earlier concerning clearances can be understood as an error of the corresponding formula. This broadens the concern to all the other deviation types, too. Because the equations are so simple they do not draw attention to many real world physical relationships which do exist in machine tools. Changing of backlash magnitude in proportion to feedrate could be explained by a stiffness of a ball-race screw and lubrication. This just creates new parameters, which expands the size of prototype matrix causing singularity problems. If we increase the number of measurements (with individual test parameters), this problem can be overcome. This is a very likely future target for development.

5.4 Co-ordinate measuring

Co-ordinate measuring has shown to involve many uncertainty sources. This experience is anticipated from the very beginning, because even the promised accuracy of a CMM is generally rather close to those a good machine tool can achieve. Besides now the analysis method is sensitive to just those errors which can be expected to be found also in a CMM. The machining process itself also includes many more uncertainties than a direct measurement.
An interesting result, however, is to notice that no significant difference can be found between the two CMMs used in the study. The analysis method masks behind itself the single point accuracy, which differs a lot in these two measuring machines. The middle grade CMM can achieve a three-dimensional uncertainty of $\pm$ (3,5 µm + 5 · 10^{-6} L) when the high grade CMM boasts with a three dimensional uncertainty of $\pm$ (0,8 µm + 1,3 · 10^{-6} L). Because the more precise machine was also newer, transferring of points from that one, was a lot easier than from the old CMM.
The stability of the results is not especially good. Even though both the co-ordinate measuring machines are located in air-conditioned rooms, the analysis results differ from time to time surprisingly much. This is not the fault of CMMs but merely of the sensitivity of the analysis method. This sensitivity shows the worst behaviour in scale errors, which on the other hand seems to be the weak point of the whole analysis system.

5.5 Deviation types

Scale mismatch and scale error behave the worst of all the deviation types. This phenomenon can mostly be explained by thermal behaviour. Scale error is most sensitive to thermal changes and temperature was not controlled in most of the measuring cases. Cross grid encoder tests had a diameter of 140 millimetres and the width of the test pieces was 120 millimetres. This means that the sample for scale error was taken from a local area of a machine tool and thus it is natural to be found so sensitive.
Squareness error should be reliable to estimate and therefore achieved results were somehow a disappointment. It seems that in some single cases not even the double ball bar and cross grid encoder give congruent results. In such cases it is probable that DBB gives erroneous results, because of some irregularities in circular interpolation. The cross grid encoder measurement offers a possibility to run consecutively along a single axis and thus the results should reveal the pure mechanical squareness.
Backlash values come off rather well in this group and the results can be considered successful. Some problems still exist because of the problems described in previous chapters, concerning lost motion. However, if a particular machine tool to be regularly tested is firstly verified to be capable of giving good values with the current method, the results can be expected to be reliable also in the future.
Servo related deviations, servo mismatch and servo lag, are difficult to compare to any other method because those do not exist. Servo mismatch value can be compared to DBB measurements and they seem to correspond to each other rather well. Results are thus satisfactory.
Lateral play values behave well on some machine tools, but in some cases they seem to wander too much. Up milling deflection is related to this error type in machining

tests. The existence of estimation of up milling deflection enables congruent results to DBB measurements but generally it slightly increases repeatability values.
Axis spike values are in this case more just for information, not to be used for compensation even if it is feasible in some controllers. The results can be seen to be satisfactory except in machined tests. The sampling rate (distance between measuring points) is not high enough on the test pieces and thus the results achieved for them are highly unreliable.
Random error (vibration) value reveals two things, namely goodness of fitting and real vibrations of a machine tool. The achieved values, however, seem to repeat themselves rather well and also to correspond to DBB results. This value is not, however, especially useful for compensation, but it can be used to follow the general condition of a machine tool.
Straightness values have a large repeatability and also they are not generally well congruent to other measurement methods either. Because straightness error was estimated by a second order curve, the expectations for this deviation type were not so great either. The most important role for this deviation is just to detect if some straightness related problems exist in a machine tool, not to reveal actual straightness values. On the other hand, capturing of pure straightness data does not require any special analysis and thus this data is easy (from analysis program point of view) to retrieve if a measurement device just supports it. The analysis program itself includes a portion to capture just simple straightness data of a linear measurement.
Measurement installation related errors: offsets, rotation, tool compensation and up milling deflection give good repeatability. This is a good situation in order to get reliable results of real deviation types. Up milling deflection has some problems discussed earlier, but because of the achieved benefits, it should still be included in the analysis set.

5.6 Further development

The system presented here has obviously some targets for development. They concern the analysis system itself and the integration of it into a shop floor control. The outlook is that this kind of an analysis system will be integrated into a shop floor control providing both feedback to an operator and automatic tuning of machine tools.

5.6.1 Details in modelling

The collection of the deviation types included in the analysis now is far away from complete. The question is: which new deviation types are significant. If many insignificant and rarely occurring deviation types are included in the model, the general behaviour of the system will deteriorate (i.e. condition of deviation matrix). On the other hand if a crucial deviation type is missing from the used model, results of the other deviation types can suffer as well [Table 16]. Collection of deviations is thus a compromise between a general good behaviour and capability to explain reality in detail.
Not all the data coming out of measurement devices is used in the analysis. The current system utilises only position, but many of the devices provide also speed and acceleration information. It is rather probable that this data could be useful in the analysis of a servo system.

Some deviation types do not even match to the current fitting procedure. Least-squares fitting cannot model frequency variations. But if the trace of deviation is regular in frequency, its phase can be found. This puts limits to a selection of deviations to be included or then else the fitting method has to be changed. This leads easily to searching algorithms and thus further to greater need of computational time.
The work in hunting more and more specific deviation types will never come to an end. This is a part of technical evolution and it creates more exact models and more exact machine tools. *Machine tools obey cause and effect relationships that are within our ability to understand and control and that there is nothing random or probabilistic about their behaviour.* [Bryan 1984]

5.6.2 Three plane model

Each plane in analysis is modelled and handled now individually. Quite a straightforward process is to combine all three planes in one set and solve it together. This just increases the size of matrix and thus extends computing time, but it should not really be the problem. This solution is a kind of 2½-dimensional model. The benefit compared to real 3-dimensional model would be that it still would not require any modelling of machine tool structure and that it would be computationally lighter. Reliability of the 2½D model could be slightly better than that of 2D model. This is because 2½D model can utilise measurement data from two planes in order to calculate the estimate for one deviation type, that improves the condition value of matrix A [chapter 3.5.2].
Five-axes machines could have some attention here too, but the model doesn't suit there so well. It is probably better to search for solutions equal to the research made in Eindhoven University [Theuws 1991][Soons 1992][Spaan 1995].

5.6.3 Workpiece follow-up in industry

Despite reliability of the results achieved from test pieces were not all satisfactory, very interesting approach is to use ordinary workpieces in a follow-up of machine tools. This requires that a suitable CMM is available and that a part of the pieces would anyhow go to inspection. Now just the measuring program is designed so that captured data points can be utilised in the analysis. This way it is possible to collect continuous condition data of machine tools without loosing machining time and at relatively low cost.

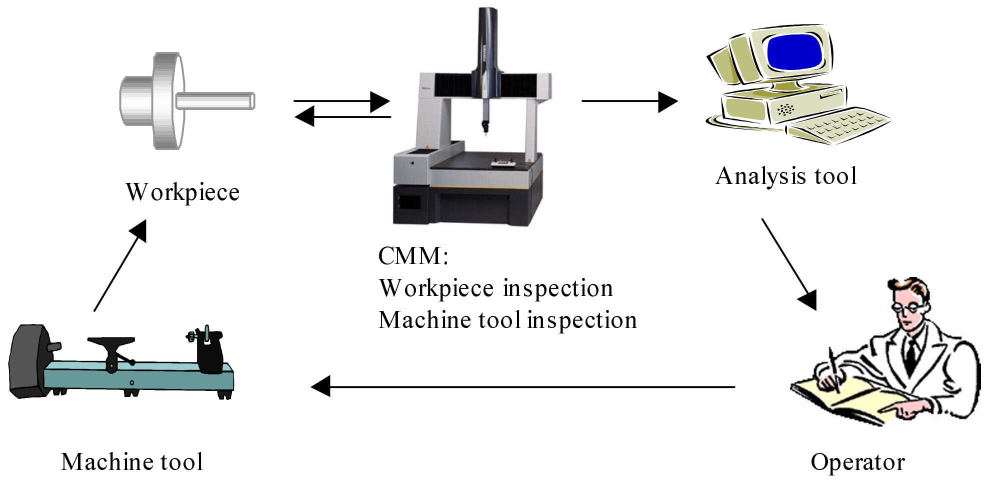


Figure 29. Workpiece in a condition monitoring of a machine tool

Practical tests can show how well the system can anticipate faults in machines and does it tell the right magnitude of deviations, if they do exist. There are rather big doubts on how this kind of a system would work, but it also offers such big benefits that it is worth while trying. There are two crucial practical aspects, which have to be solved before any other actions, namely the easy integration to CMM measurement results and checking that features suitable for analysis exist on workpieces. It is probable that the results do not at once correlate well to direct measurement, but some kind of calibration or determination of reliability for each individual machine tool have to be performed first.
The system works best if CMM is integrated in a production system, i.e. it is part of a FMS (flexible manufacturing system). This way feedback is achieved fast and even more important is that production related data stays attached to a measured piece. Always, when a workpiece is taken out of a system there exists a certain risk of some crucial information being lost or misinterpreted. Integrated CMM solves most of these problems and makes the measuring process repeatable.

5.6.4 Automated data collection and analysis

In order to get out the full power of the analysis system, measurements should definitely be automated. Automated measurements could be run at night or during some other idle time. Measuring run should take no more than 15 minutes of machine time. Short measuring cycle and no human set-up time would enable frequent inspections. When this kind of device would be part of a FMS, it could economically serve many machine tools and the whole measuring-analysis-monitoring-compensation cycle could be automated [chapter 2.3.3].
A single measuring device placed in a storage pallet could serve all machining centres attached to a system. A device would consist of two main parts. The actual measuring instrument would be located on a pallet. This is the intelligent part of the system. Every machine tool would then have just a simple attaching tool in their magazines.
The device itself could be implemented using either design principles of Uni-Test [chapter 2.1.4] or laser ball bar [chapter 2.1.8]. These both have possibility to enisle all the measuring components on the pallet side and they can perform free-form test runs.

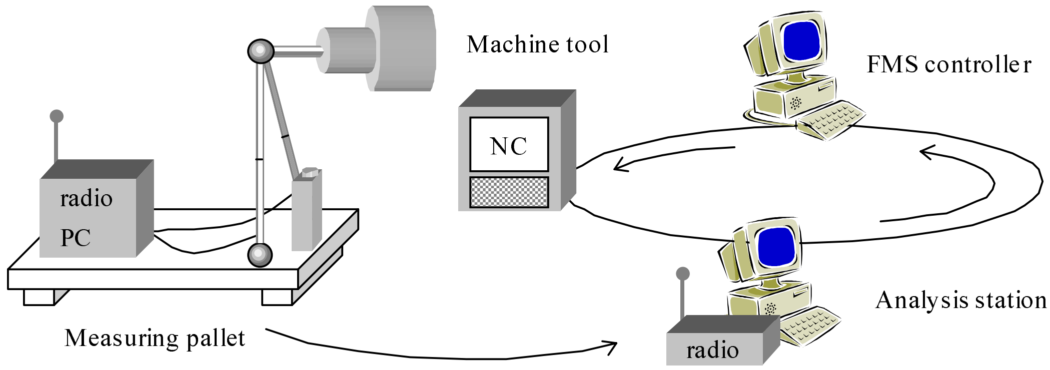


Figure 30. Automatic measurement in FMS

A FMS controller has in its work queue orders for regular machine tool inspections with a low priority. The measuring pallet and corresponding NC-program of a test run are transferred to a machine tool in the same way as an ordinary workpiece. A touch of a spindle would first wake up the measurement device. The spindle would then attach to the actuator of the measuring device and perform the test run. During the run a simple computer on a pallet would collect data and send it via a radio LAN (local area network) to the analysis and follow-up station. Data is analysed there and if necessary a new compensation table is composed. The new compensation table is transferred to a numerical controller via FMS controller as it were an ordinary NC-program [Pihlanen and Torvinen 1997]. After compensation is activated a second measurement for verification can be accomplished.

6 CONCLUSIONS

A universal method for evaluation of machine tool measurements is presented in this work. The method can analyse a variety of measurements that include dynamically captured data points but have them just in one plane. The great potential of the analysis system lies in enabling an automated follow-up of parametric errors in machine tools. The concrete objectives of the thesis work, which are set in chapter 1.5, are achieved as follows:

1. *Create theory for analysis*
   The new theory is developed based on the work done earlier for circular tests. The theory is expanded for test pieces and linear features.
2. *Develop software based on the theory*
   The analysis program [appendix 15] is developed and tested during the work with empirical cases.
3. *Show that the analysis system gives consistent results for different direct measurement methods*
   It is shown that different direct measurement methods with different test paths can give consistent results.
4. *Show that direct free form measurements can be used instead of test pieces*
   It is shown that direct free form measurements do not necessarily give consistent results with test pieces.

It is shown that this way different measuring methods can be used side by side and they can offer comparable results. However, some reservations about this statement are found as well. Direct measurements and indirect measurement do not necessarily give congruent results. The same can even occur between different direct measurement methods. This leads to the conclusion that the current method should be calibrated individually for each machine tool in which it would be used for automatic monitoring. Calibration means here comparison between direct and indirect measuring methods.

Inevitably static and dynamic measurements behave differently and they can reveal different deviation types in a machine tool as well. Dynamic measurements have this far faced the problem that no proper analysis system has been available to evaluate them. This work offers now one method to evaluate them in order to reveal parametric errors in a machine tool.

Cross grid encoder [chapter 2.1.2] has been shown to be a powerful tool to determine error sources in machine tools. It is not only for inspection of geometry (indeed some more suitable tools for this purpose do exist), but it enables machine tool builders to see deep down the actual motion of their machines. Because of a high sampling rate and good accuracy it fits very well for tuning servos.

Once again the great importance of thermal expansion is being shown. Without control of thermal conditions all the other actions to improve accuracy are doomed to fail. However, the philosophy of this work is to separate geometrical and servo errors from thermally induced deviations [Figure 1]. Thermal control or compensation should be completed as a task that is integrated to a machine tool itself. Inspection of geometrical errors and servo tuning should instead be made with an external device. Thermal compensation values can be updated every 10 minutes when geometrical compensation tables hardly would be updated more often than once a month.

Interesting work in the future is integration of the proposed analysis method in a flexible manufacturing system. CMM or external automatic measuring pallet could take care of the actual measuring process. An analysis station offers monitoring information on the status of machine tools and creates compensation tables when necessary. A FMS controller schedules inspections, offers test programs and activates new compensations.

References

Aboud-Zeid A., Bechstein K.-H., Enghave C. and Kunzmann H, A Multichannel Diode Laser Interferometer for Displacement Measurement on a CMM, Annals of the CIRP, Vol. 45/1, 1996, pp. 489-492

Andersson P.H., Methodology for evaluating the production accuracy of machine tools, PhD thesis, Tampere University of Technology, 1992, 121p.

ANSI/ASME B5.54-1992, Methods for Performance, Evaluation of Computer Numerically Controlled Machining Centres, 1992 (reaffirmed 1998), 154p.

ANSI/CAM-I 101-1995 Dimensional Measuring Interface Standard Revision 3.0, CAM-I Inc, Texas USA, 1995, 389p.

BAS Machine Tests, Edition 1, AB Bofors, Alfa-Laval AB, Asea, Saab-Scania, Sveriges Mekanförbund

Bryan J.B., A simple method for testing measuring machines and machine tools, Part 1: Principles and applications, Precision Engineering, Vol. 4 No 2, 1982, pp. 61-69

Bryan J.B., The power of deterministic thinking in machine tool accuracy (preprint of LLNL: UCRL-91531), First International Machine Tool Engineers Conference, Tokyo Japan, 1984, 15p.

Bryan J.B., International status of thermal error research, Annals of the Cirp, Vol. 39/2, 1990, pp. 645-656

Denavit J. and Hartenberg R.S., A kinematic notation for lower-pair mechanisms based on matrices, ASME Journal of Applied Mechanics, June 1955, pp. 215-221

DIN 8601, Abnahmebedingungen für Werkzeugmaschinen für die spanende Bearbeitung von Metallen, 1988,27p.

Donmez M.A., Blomquist D.S., Hocken R.J., Liu C.R. and Barash M.M., A general methodology for machine tool accuracy enhancement by error compensation, Precision Engineering, Vol. 8 No 4, 1986, pp. 187-196

Donmez M.A., Development of virtual machine tools, Proceedings of the Third International Conference on Progress of Cutting and Grinding, Osaka Japan, 1996, pp. 8-13

Ferreira P.M. and Liu C.R., A contribution to the analysis and compensation of the geometric error of a machining center, Annals of the Cirp, Vol. 35/1, 1986, pp. 259-262

Ferreira P.M. and Liu C.R., A method for estimating and compensating quasistatic errors of machine tools, Journal of Engineering for Industry, Vol. 115, 1993, pp. 149-159

Haas F., Entwicklung eines neuen Meßgerätes zur automatisierten Schnellabnahme-prüfung von CNC-Maschinen, PhD thesis, Institut für Fertigungstechnik, TU Graz, Austria, 1996, 145p.

Heidenhain 1998, Measuring systems for machine tool inspection and acceptance testing, Dr. Johannes Heidenhain GmbH, Traunreut Germany, 8/1998, 15p.

Hölsä J. 1997a, Feature Based Analysis of Machine Tools, in XIV Imeko World Congress, Proceedings of the New Measurements - Challenges and Visions XIV Imeko World Congress, Vol. 8, Tampere Finland, 1997, pp. 52-57

Hölsä J. 1997b, Analysis of machine tool deviations, Proceedings of the Comadem '97, Vol. 2, Espoo Finland, 1997, pp. 515-523

Hölsä J. 1997c, Utilizing CMM Measurements in the Evaluation of Machine Tool Accuracy, 3rd International conference on Laser Metrology and Machine Performance, Huddersfield UK, 1997, pp. 487-496

ISO 10791-7, Test conditions for machining centres – Part 7: Accuracy of a finished test piece, International Organisation for Standardisation, Geneva Switzerland, 1997, 12p.

ISO 230-2, Test code for machine tools – Part 2: Determination of accuracy and repeatability of positioning of numerically controlled machine tool axes, International Organisation for Standardisation, Geneva Switzerland, 1997, 15p.

ISO/DIS 230-3, Test code for machine tools – Part 3: Determination of thermal effects, International Organisation for Standardisation, Geneva Switzerland, 1998, 38p.

ISO 230-4, Test code for machine tools - Part 4: Circular tests for numerically controlled machine tools International Organisation for Standardisation, Geneva Switzerland, 1996, 12p.

ISO 3070/II, Test conditions for boring and milling machines with horizontal spindle – Testing of the accuracy – Part II: Floor type machines, International Organisation for Standardisation, Geneva Switzerland, 1978, 27p.

ISO /TC3/WG10, Substitution method to make traceable measurements with coordinate measuring machines, working paper, International Organisation for Standardisation, Geneva Switzerland, 1996, 19p.

Järvinen P. and Järvinen A., Tutkimustyön metodeista (in Finnish), Tampereen yliopisto, Tampere Finland, 1993, 121p.

Kakino Y., Ihara Y., Shinohara A., Accuracy Inspection of NC Machine Tools by Double Ball Bar Method, Carl Hanser Verlag, Munich Germany, 1993, 189p.

Knapp W. and Hrovat S., The circular test, S. Hrovat, Zurich Switzerland, 1987, 186p.

Knapp W., Vicha J., Moergeli A., Jäger G., Kreisformtest für hohe Bahngeschwindigkeiten, Werkstatt und Betrieb, Vol. 10, 1994, pp. 790-794.

Knapp W., Interim checks for machine tools, 3rd International conference on Laser Metrology and Machine Performance, Huddersfield UK, 1997, pp. 161-168

Krulewich D., Rapid mapping of volumetric machine errors using distance measurements, Proceedings of International Seminar on Improving Machine Tool Performance, San Sebastian Spain, Vol. 2, 1998, pp. 487-496

Ling A., Thermal error modeling of machine tools using neural networks, Proceedings for an International Multidisciplinary Conference Intelligent Systems: A Semiotic Perspective, Gaithersburg (MD) USA, 1996, 7p.

Liotto G. and Wang C.P., Laser Doppler displacement meter (LDDM) allows new diagonal measurement for large aspect ratio machine tool easily and accurately, 3rd International conference on Laser Metrology and Machine Performance, Huddersfield UK, 1997, pp. 187-194

Love W. and Scarr A., The determination of the volumetric accuracy of multi-axis machines, Proceedings of the 14th MTDR Conference, Manchester UK, 1973, pp. 307-315

Mahbubur R., Heikkala J., Lappalainen K. and Karjalainen J., Positioning accuracy improvement in five-axis milling by post processing, International Journal of Machine Tools and Manufacture, Vol. 37 No 2, 1997, pp. 223-236

Meitz K., Ein neues Meßgerät zur kombinierten statischen und dynamischen Geometrieanalyse unkonventioneller Werkzeugmaschinenstrukturen, PhD thesis, Institut für Fertigungstechnik, TU Graz, Austria, 1999, 115p.

Mou J., Donmez M.A. and Cetinkunt S. An adaptive error correction method using feature-based analysis techniques for machine performance improvement, Part 1 & 2, Journal of Engineering for Industry, Vol. 117, 1995, pp. 584-600

NAS 979, Uniform cutting tests – NAS series: Metal cutting equipment specifications, Aerospace Industries Association of America, Washington DC. USA, 1969, 59p.

Ni J. and Wu S.M., An on-line measurement technique for machine volumetric error compensation, Journal of Engineering for Industry, Vol. 115, 1993, pp. 85-92

Oksanen P., Kaksoisnivelsauvamittaus koneistuskeskuksen tarkastuksessa ja kunnonseurannassa (in Finnish), Lic. Tech. Thesis, Tampere University of Technology, 1996, 167p.

Pihlanen R. and Torvinen S., Automated machine tool error compensation on PC-based numerical controllers, Proceedings of the 14th International Conference on Production Research, Vol. 2, Osaka Japan, 1997, pp. 1570-1573

Prenninger J.P., Filz K.M., Vincze M. and Gander H. Real-time contactless measurement of robot pose in six degrees of freedom, Measurement, Vol. 14, 1995, pp. 255-264

Schellekens P., Rosielle N., Vermeulen H., Vermeulen M., Wetzels S. and Pril W., Design for precision: Current status and trends, Annals of the CIRP, Vol. 47 No 2, 1998, pp. 557-586

Schmitz T. and Ziegert J., Premachining computer numerical control contour validation, Precision Engineering, Vol. 22 No 1, 1998, pp. 10-18

SFS-EN ISO 9001, Quality systems. Model for quality assurance in design, development, production, installation and servicing, Suomen Standardisoimisliitto SFS r.y., Helsinki Finland, 1994, 29p.

Soons J.A., Theuws F. C. and Schellekens P.H., Modelling the errors of multi-axis machines: a general methodology, Precision Engineering, Vol. 14 No 1, 1992, pp. 5-19

Soons J.A., Error analysis of a hexapod machine tool, 3rd International conference on Laser Metrology and Machine Performance, Huddersfield UK, 1997, pp. 347-358

Spaan H.A.M, Software Error Compensation of Machine Tools, PhD thesis, University of Eindhoven, Netherlands, 1995, 166p.

Tajbakhsh H., Abadin Z. and Ferreira P.M., L_∞ parameter estimates for volumetric error in models of machine tools, Precision Engineering, Vol. 20 No 3, 1997, pp. 179-187

Takamasu K., Guo B-W., Furutani R. and Ozono S., Basic concept of feature based metrology, Proceedings of 6th Imeko Symposium: Metrology for quality control in production, Vienna Austria, 1998, pp. 637-642

Takeuchi Y. and Watanabe T., Generation of 5-axis control collision-free tool path and postprocessing for NC data, Annals of the CIRP, Vol. 41 No 1, 1992, pp.539-542

Theuws F.C., Enhancement of machine tool accuracy: Theory and implementation, PhD thesis, University of Technology Eindhoven, Netherlands, 1991, 197p.

Tlusty J., Comments to the paper of Kurtoglu A. and Sohlenius G., Annals of the CIRP, Vol. 39/2, 1990, p. 722

Torvinen S., Hölsä J. and Gu K.Y., Using mathematical methods, neural nets and case based reasoning in the analysis of machine tool quick tests, Proceedings of the 6th International DAAAM Symposium, Krakova Poland, 1995, 2p.

Wang C. and Griffin B., Non-contact circular test using a laser/ballbar, publicity material of Optodyne Inc., Compton California USA, 1999, 13p.

Weck M., McKeown P., Bonse R. and Herbst U., Reduction and compensation of thermal errors in machine tools, Annals of the CIRP, Vol. 44/2, 1995, pp. 589-598

Zhang B., Li Y. and Zhuang Y., Reducing the thermal deformations of machine tools by heat pipes, Proceedings of the CIRP, Sept. 1991, pp. 651-662

Appendices

Abbreviations, units and formulae used in appendices

Measurement ID-number look-up table

ID	Name	Machine	Device	Comment	Date	Feed mm/min
60	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 16:23:20	2000,00
61	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 18:25:44	2000,00
62	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 16:29:26	400,00
63	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 18:31:41	400,00
64	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 21:47:56	10000,00
65	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 21:06:36	2000,00
66	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 21:41:43	2000,00
67	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 21:12:06	400,00
68	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 21:26:41	400,00
69	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 20:13:27	2000,00
70	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 20:15:52	2000,00
71	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 20:39:40	400,00
72	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 20:21:51	400,00
85	Daewoo / Fastems	Daewoo ACE-H50X	Grid Encoder	G64 (default)	1.10.1997 17:30:21	400,00
86	Daewoo / Fastems	Daewoo ACE-H50X	Grid Encoder	G61	1.10.1997 17:15:44	2000,00
87	Daewoo / Fastems	Daewoo ACE-H50X	Grid Encoder	G61	2.10.1997 10:54:10	400,00
88	Daewoo / Fastems	Daewoo ACE-H50X	Grid Encoder	G61	2.10.1997 10:48:34	2000,00
89	Daewoo / Fastems	Daewoo ACE-H50X	Grid Encoder	G61	2.10.1997 9:48:58	400,00
90	Daewoo / Fastems	Daewoo ACE-H50X	Grid Encoder	G61	2.10.1997 9:32:54	2000,00
91	Makino A77 / Instrumentarium	Makino A77	Grid Encoder		19.12.1997 9:40:11	400,00
92	Makino A77 / Instrumentarium	Makino A77	Grid Encoder		19.12.1997 9:43:44	2000,00
93	Makino A77 / Instrumentarium	Makino A77	Grid Encoder		19.12.1997 10:39:22	400,00
94	Makino A77 / Instrumentarium	Makino A77	Grid Encoder		19.12.1997 10:34:05	2000,00
95	Makino A77 / Instrumentarium	Makino A77	Grid Encoder		19.12.1997 11:56:32	400,00
96	Makino A77 / Instrumentarium	Makino A77	Grid Encoder		19.12.1997 11:58:47	2000,00
97	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Piece 1 - Daewoo	12.12.1997 8:42:38	400,00
98	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Stepwise change	12.12.1997 8:45:56	400,00
99	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Stepwise change	12.12.1997 8:48:34	400,00
100	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Piece 4 - Daewoo	12.12.1997 8:50:56	400,00
101	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Stepwise change	12.12.1997 8:54:06	800,00
102	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Stepwise change	12.12.1997 8:59:06	800,00
103	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Piece 7 - Daewoo	12.12.1997 9:02:30	800,00
104	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Stepwise change	12.12.1997 9:05:10	800,00
105	Daewoo / Fastems	Daewoo ACE-H50X	CMM	Piece 9 - Daewoo	12.12.1997 9:07:44	800,00
106	Makino A55 / TTEK	Makino A55	CMM	Piece 1 - Makino	12.11.1997 18:30:06	400,00

107	Makino A55 / TTEK	Makino A55	CMM	Piece 2 - Makino	12.11.1997 19:23:24	2000,00
109	Makino A55 / TTEK	Makino A55	CMM	Piece 3 - Makino	12.11.1997 19:29:04	400,00
110	Makino A55 / TTEK	Makino A55	CMM	Piece 4 - Makino	12.11.1997 19:41:34	2000,00
111	Makino A55 / TTEK	Makino A55	CMM	Piece 5 - Makino	12.11.1997 19:45:28	2000,00
112	Makino A55 / TTEK	Makino A55	CMM	Piece 6 - Makino	12.11.1997 19:50:00	400,00
113	Makino A55 / TTEK	Makino A55	CMM	Piece 7 - Makino	12.11.1997 19:54:06	4000,00
114	Makino A55 / TTEK	Makino A55	CMM	Piece 8 - Makino	12.11.1997 20:00:26	400,00
115	Makino A55 / TTEK	Makino A55	CMM	Piece 9 - Makino	12.11.1997 20:04:50	400,00
116	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 11:32:42	400,00
117	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder	G61.1 path correction	9.1.1998 11:38:09	2000,00
118	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder	G61.1 path correction	9.1.1998 11:41:46	10000,00
119	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 12:59:37	400,00
120	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 12:53:30	10000,00
121	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 12:52:37	2000,00
122	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 12:12:59	400,00
123	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 12:04:47	2000,00
124	Mazak FH480X / TKK	Mazak FH480X	Grid Encoder		9.1.1998 12:06:06	10000,00
125	Makino A55 / TTEK	Makino A55	CMM	Piece 2 - Makino	8.4.1998 16:13:46	2000,00
126	Makino A77 / Instrumentarium	Makino A77	CMM	Piece 1 - Makino A77	8.4.1998 16:03:40	400,00
127	Makino A55 / repeats	Makino A55	CMM	Piece 4 - Makino	13.5.1998 8:52:14	2000,00
128	Makino A55 / repeats	Makino A55	CMM	Piece 9 - Makino	13.5.1998 8:38:56	400,00
129	Daewoo / renewal	Daewoo ACE-H50X	CMM	Piece 6 - Daewoo	13.5.1998 8:49:40	800,00
130	Daewoo / renewal	Daewoo ACE-H50X	CMM	Piece 3 - Daewoo	13.5.1998 8:47:04	400,00
131	Daewoo / renewal	Daewoo ACE-H50X	CMM	Piece 2 - Daewoo	13.5.1998 8:42:46	400,00
132	Daewoo / renewal	Daewoo ACE-H50X	CMM	Piece 8 - Daewoo	13.5.1998 8:36:10	800,00
133	Daewoo / renewal	Daewoo ACE-H50X	CMM	Piece 5 - Daewoo	13.5.1998 8:31:56	800,00
134	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino	24.7.1998 11:25:56	2000,00
135	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino	24.7.1998 11:30:00	2000,00
136	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino	24.7.1998 11:33:58	2000,00
137	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino	24.7.1998 11:37:52	2000,00
138	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino - CMM Batch	28.7.1998 10:01:24	2000,00
139	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino - CMM Batch	28.7.1998 9:48:50	2000,00
140	Makino A55 / 2nd repeats	Makino A55	CMM	Piece 2 - Makino - CMM Batch	28.7.1998 10:09:50	2000,00
141	Makino A55 / Zeiss	Makino A55	CMM	Piece 2 - Makino - Zeiss	3.8.1998 8:44:30	2000,00
142	Makino A55 / Zeiss	Makino A55	CMM	Piece 2 - Makino - Zeiss	3.8.1998 9:21:02	2000,00
143	Makino A55 / Zeiss	Makino A55	CMM	Piece 2 - Makino - Zeiss	3.8.1998 9:21:10	2000,00
144	Makino A55 / Zeiss	Makino A55	CMM	Piece 2 - Makino - Zeiss	3.8.1998 9:21:18	2000,00
145	Makino A55 / Zeiss	Makino A55	CMM	Piece 2 - Makino - Zeiss	3.8.1998 9:21:28	2000,00
146	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Grid Encoder		28.8.1998 18:27:32	400,00
147	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Grid Encoder		28.8.1998 18:22:15	2000,00
148	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Grid Encoder		28.8.1998 16:18:45	400,00

149	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Grid Encoder		28.8.1998 16:06:46	2000,00
150	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Grid Encoder		28.8.1998 17:11:54	400,00
151	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Grid Encoder		28.8.1998 17:06:45	2000,00
152	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Very first piece	7.9.1998 17:00:47	400,00
153	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Cold machine	7.9.1998 17:02:00	400,00
154	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Warm machine - 1. measurement	7.9.1998 17:02:38	400,00
155	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Warm machine - 2. measurement	7.9.1998 17:03:06	400,00
156	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Warm machine - 3. measurement	7.9.1998 17:03:40	400,00
157	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Warm machine - 4. measurement	7.9.1998 17:04:18	400,00
158	Mitsui Seiki / OY test piece	Mitsui Seiki	CMM	Warm machine - 5. measurement	7.9.1998 17:06:40	400,00
159	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar	1. measurement	10.9.1998 13:39:07	400,00
160	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar	2. measurement	10.9.1998 13:53:58	400,00
161	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar		10.9.1998 13:54:59	2000,00
162	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar		10.9.1998 13:56:33	400,00
163	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar		10.9.1998 13:57:31	2000,00
164	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar		10.9.1998 13:58:55	400,00
165	Mitsui Seiki / OY 28-08-1998	Mitsui Seiki	Double Ball Bar		10.9.1998 13:59:54	2000,00
174	OKK / TAKK	OKK MCH-450	Grid Encoder		5.11.1997 15:14:09	400,00
175	OKK / TAKK	OKK MCH-450	Grid Encoder		5.11.1997 15:15:51	2000,00
176	OKK / TAKK	OKK MCH-450	Grid Encoder		5.11.1997 13:52:25	400,00
177	OKK / TAKK	OKK MCH-450	Grid Encoder		5.11.1997 13:54:41	2000,00
178	OKK / TAKK	OKK MCH-450	Grid Encoder		5.11.1997 14:37:45	400,00
179	OKK / TAKK	OKK MCH-450	Grid Encoder		5.11.1997 14:41:28	2000,00
180	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 21:12:06	400,00
181	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 21:26:41	400,00
182	Makino A55 / TTEK	Makino A55	Grid Encoder	G64	13.10.1997 21:06:36	2000,00
183	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 21:41:43	2000,00
184	Makino A55 / TTEK	Makino A55	Grid Encoder	G61	13.10.1997 21:47:56	10000,00

Conversion of DBB results

DBB measurements are analysed by Renishaw Ballbar Data Analysis 4.21. The following scaling has been used to make results comparable.

Cyclic magnitude:	*uniform cyclic = (cyclic in minus end + cyclic in positive end) / 2*
Lateral play:	*uniform play = (play in minus end + play in plus end) / 2*
Reversal spike:	*uniform spike = (spike in minus end + spike in plus end) / 2*
Scale mismatch:	*relative* scale *mismatch = (relative scale error in 1st axis) – (relative scale error in 2nd axis)*
Servo mismatch:	*relative servo mismatch [µm/(mm/s)] = - delay between axes [ms]*
Squareness:	*squareness [arcsec] = 0,648 / π * squareness [µm/m]*
Straightness:	*relative straightness [µm/m] = straightness in test [µm] / test diameter [m]*

Formulae in statistics

Calculation of difference:

$$d_i = x_i - \bar{x}$$

Calculation of standard deviation:

$$s = \sqrt{\frac{1}{n}\sum_{i=1}^{n} d_i^2}$$

Calculation of uncertainty:

$$U = 2s$$

Legend

Caption	Unit	Description
Squareness	arcsec	squareness error between two axes
Scale	µm/m	scale mismatch between two axes
Scale H	µm/m	scaling error of the first axis
Scale V	µm/m	scaling error of the second axis
Back PH	µm	backlash at positive end of the first axis
Back PV	µm	backlash at positive end of the second axis
Back MH	µm/m	backlash at negative end of the first axis
Back MV	µm/m	backlash at negative end of the second axes
Straight H	µm/m	straightness error of the first axis estimated by a parabola
Straight V	µm/m	straightness error of the second axis estimated by a parabola
Servo Mismatch	µm/(maximum feedrate[mm/s])	servo amplification mismatch between two axes
Servo Lag	µm/(max{feedrate^2/radius})	error in arcs due inadequate servo amplification
Cyclic H	µm	magnitude of observed cyclical error in the first axis
Cyclic V	µm	magnitude of observed cyclical error in the second axis
Pitch H	mm	pitch of observed cyclical error in the first axis
Pitch V	mm	pitch of observed cyclical error in the second axis
Phase H	° degrees	phase of observed cyclical error in the first axis
Phase V	° degrees	phase of observed cyclical error in the second axis
Spike H	µm	axis reversal spike in the first axis
Spike V	µm	axis reversal spike in the second axis
Play H	µm	play of the first axis
Play V	µm	play of the second axis
Random	µm	magnitude of vibration
Compensation	µm	tool radius compensation error
Upmilling	µm	deflection of up milling compared to down milling

Repeatability of cross grid encoder measurements

Grid encoder Makino xy 400 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
62	-1,94	-1,70	14,69	16,40	0,26	1,99	0,86	2,07	-4,58	-2,63	0,14	1,67	0,29	0,92	0,64	1,19	-0,10	0,28	0,22	0,00	G64
63	-2,42	-2,35	18,22	20,57	0,09	2,07	0,77	2,19	-4,76	-2,20	0,13	1,76	0,32	0,82	0,82	1,02	-0,08	0,29	0,21	0,00	G61
Average	**-2,18**	**-2,03**	**16,46**	**18,49**	**0,18**	**2,03**	**0,82**	**2,13**	**-4,67**	**-2,42**	**0,14**	**1,72**	**0,31**	**0,87**	**0,73**	**1,11**	**-0,09**	**0,29**	**0,21**	**0,00**	
Difference	**0,24**	**0,33**	**1,77**	**2,09**	**0,09**	**0,04**	**0,05**	**0,06**	**0,09**	**0,22**	**0,01**	**0,05**	**0,02**	**0,05**	**0,09**	**0,09**	**0,01**	**0,01**	**0,01**	**0,00**	

Grid encoder Makino xy 2000 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
60	-1,89	1,78	11,33	9,55	0,13	1,61	0,87	1,67	-3,48	-1,06	0,02	0,35	0,07	0,77	1,43	3,31	-0,02	0,23	0,32	0,00	G64
61	-2,48	-0,51	15,64	16,14	0,09	1,87	0,91	2,09	-3,11	-0,82	0,02	0,36	0,02	0,76	1,36	3,54	-0,12	0,24	0,28	0,00	G61
Average	**-2,19**	**0,64**	**13,49**	**12,85**	**0,11**	**1,74**	**0,89**	**1,88**	**-3,30**	**-0,94**	**0,02**	**0,36**	**0,05**	**0,77**	**1,40**	**3,43**	**-0,07**	**0,24**	**0,30**	**0,00**	
Difference	**0,30**	**1,15**	**2,16**	**3,30**	**0,02**	**0,13**	**0,02**	**0,21**	**0,19**	**0,12**	**0,00**	**0,01**	**0,03**	**0,01**	**0,04**	**0,12**	**0,05**	**0,01**	**0,02**	**0,00**	

Grid encoder Makino xz 400 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
67	-3,66	-17,77	15,79	33,56	-0,21	-0,38	0,71	0,35	-5,02	-0,79	0,16	1,93	0,33	0,74	0,62	0,85	-0,06	-0,17	0,41	0,00	G64
68	-3,55	-15,64	15,93	31,57	-0,33	0,09	0,58	0,24	-5,01	-0,94	0,12	1,82	0,64	1,12	0,59	0,74	0,01	-0,17	0,52	0,00	G61
Average	**-3,61**	**-16,71**	**15,86**	**32,57**	**-0,27**	**-0,15**	**0,65**	**0,30**	**-5,02**	**-0,87**	**0,14**	**1,88**	**0,49**	**0,93**	**0,61**	**0,80**	**-0,03**	**-0,17**	**0,47**	**0,00**	
Difference	**0,06**	**1,07**	**0,07**	**1,00**	**0,06**	**0,24**	**0,07**	**0,06**	**0,01**	**0,08**	**0,02**	**0,06**	**0,16**	**0,19**	**0,02**	**0,06**	**0,04**	**0,00**	**0,06**	**0,00**	

Grid encoder Makino xz 2000 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
65	-3,55	-16,63	17,71	34,34	0,21	-0,32	1,04	0,08	-5,75	-1,21	0,04	0,39	0,42	0,60	1,91	2,54	0,02	-0,27	0,64	0,00	G64
66	-3,61	-17,14	16,90	34,05	0,32	-0,39	0,80	0,09	-5,96	-1,26	0,05	0,39	0,42	0,64	2,77	3,34	0,00	-0,22	0,45	0,00	G61
Average	**-3,58**	**-16,89**	**17,31**	**34,20**	**0,27**	**-0,36**	**0,92**	**0,09**	**-5,86**	**-1,24**	**0,05**	**0,39**	**0,42**	**0,62**	**2,34**	**2,94**	**0,01**	**-0,25**	**0,55**	**0,00**	
Difference	**0,03**	**0,26**	**0,41**	**0,15**	**0,06**	**0,09**	**0,12**	**0,01**	**0,11**	**0,03**	**0,01**	**0,00**	**0,00**	**0,02**	**0,43**	**0,40**	**0,01**	**0,03**	**0,10**	**0,00**	

Grid encoder Makino yz 400 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
71	0,96	1,05	33,18	32,13	2,52	0,18	2,89	0,34	-6,23	6,36	0,08	2,56	0,93	0,49	2,41	0,61	-0,17	-0,53	0,60	0,00	G64
72	0,83	-0,20	32,52	32,72	2,52	0,22	2,75	0,38	-6,50	6,96	0,07	2,62	0,86	0,48	2,39	0,61	-0,13	-0,54	0,53	0,00	G61
Average	**0,90**	**0,43**	**32,85**	**32,43**	**2,52**	**0,20**	**2,82**	**0,36**	**-6,37**	**6,66**	**0,08**	**2,59**	**0,90**	**0,49**	**2,40**	**0,61**	**-0,15**	**-0,54**	**0,57**	**0,00**	
Difference	**0,07**	**0,63**	**0,33**	**0,30**	**0,00**	**0,02**	**0,07**	**0,02**	**0,14**	**0,30**	**0,01**	**0,03**	**0,04**	**0,01**	**0,01**	**0,00**	**0,02**	**0,01**	**0,04**	**0,00**	

Grid encoder Makino yz 2000 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
69	2,24	4,56	36,53	31,97	3,38	1,41	1,80	-0,31	-10,32	13,10	0,00	0,41	1,23	0,82	5,72	4,39	-0,10	-0,98	0,62	0,00	G64
70	0,73	3,47	37,90	34,42	2,33	0,78	2,32	0,75	-7,01	8,70	0,01	0,43	0,93	0,28	5,19	2,95	-0,25	-0,71	0,73	0,00	G61
Average	**1,49**	**4,02**	**37,22**	**33,20**	**2,86**	**1,10**	**2,06**	**0,22**	**-8,67**	**10,90**	**0,01**	**0,42**	**1,08**	**0,55**	**5,46**	**3,67**	**-0,18**	**-0,85**	**0,68**	**0,00**	
Difference	**0,76**	**0,55**	**0,69**	**1,23**	**0,53**	**0,32**	**0,26**	**0,53**	**1,66**	**2,20**	**0,01**	**0,01**	**0,15**	**0,27**	**0,27**	**0,72**	**0,08**	**0,14**	**0,06**	**0,00**	

Statistical analysis of cross grid encoder repeatability

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
Xy 400	0,24	0,33	1,77	2,09	0,09	0,04	0,05	0,06	0,09	0,22	0,01	0,05	0,02	0,05	0,09	0,09	0,01	0,01	0,01	0,00
Xy 2000	0,30	1,15	2,16	3,30	0,02	0,13	0,02	0,21	0,19	0,12	0,00	0,01	0,03	0,01	0,04	0,12	0,05	0,01	0,02	0,00
Xz 400	0,06	1,07	0,07	1,00	0,06	0,24	0,07	0,06	0,01	0,08	0,02	0,06	0,16	0,19	0,02	0,06	0,04	0,00	0,06	0,00
Xz 2000	0,03	0,26	0,41	0,15	0,06	0,09	0,12	0,01	0,11	0,03	0,01	0,00	0,00	0,02	0,43	0,40	0,01	0,03	0,10	0,00
Yz 400	0,07	0,63	0,33	0,30	0,00	0,02	0,07	0,02	0,14	0,30	0,01	0,03	0,04	0,01	0,01	0,00	0,02	0,01	0,04	0,00
Yz 2000	0,76	0,55	0,69	1,23	0,53	0,32	0,26	0,53	1,66	2,20	0,01	0,01	0,15	0,27	0,27	0,72	0,08	0,14	0,06	0,00
Maximum	**0,76**	**1,15**	**2,16**	**3,30**	**0,53**	**0,32**	**0,26**	**0,53**	**1,66**	**2,20**	**0,02**	**0,06**	**0,16**	**0,27**	**0,43**	**0,72**	**0,08**	**0,14**	**0,10**	**0,00**
Deviation	**0,35**	**0,75**	**1,19**	**1,73**	**0,22**	**0,18**	**0,13**	**0,24**	**0,69**	**0,91**	**0,01**	**0,03**	**0,09**	**0,14**	**0,21**	**0,34**	**0,04**	**0,06**	**0,06**	**0,00**
Uncertainty	**0,70**	**1,50**	**2,38**	**3,46**	**0,44**	**0,36**	**0,26**	**0,48**	**1,38**	**1,82**	**0,03**	**0,07**	**0,18**	**0,28**	**0,42**	**0,68**	**0,08**	**0,12**	**0,11**	**0,00**

Repeatability of test piece measurements

Makino test piece
400 mm/min
0,4 mm finishing

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
106	-3,29	6,56	45,80	39,24	-0,81	-0,06	-0,21	0,69	-6,10	-0,80	0,50	2,41	1,40	0,72	2,85	3,34	-4,12	0,72	3,12	12,65	-10,30
109	-2,67	18,01	60,01	42,00	-0,74	0,73	0,34	1,41	-7,36	-0,54	0,48	4,12	1,48	0,17	3,43	2,46	-5,18	1,85	3,13	14,33	-11,55
112	8,15	-34,18	25,90	60,09	-5,04	1,04	-0,21	3,79	1,12	2,54	-0,25	-0,55	1,94	1,98	2,77	4,17	-1,59	1,06	6,10	13,40	-10,05
114	6,26	-46,81	13,32	60,12	-5,97	2,56	-1,02	5,86	-4,96	1,71	-0,53	-0,33	1,96	0,80	1,43	4,94	2,49	-2,41	5,92	13,83	-5,22
Average	**2,11**	**-14,11**	**36,26**	**50,36**	**-3,14**	**1,07**	**-0,28**	**2,94**	**-4,32**	**0,73**	**0,05**	**1,41**	**1,69**	**0,92**	**2,62**	**3,73**	**-2,10**	**0,31**	**4,57**	**13,55**	**-9,28**
Deviation	**5,14**	**27,07**	**17,95**	**9,79**	**2,39**	**0,95**	**0,49**	**2,04**	**3,26**	**1,43**	**0,45**	**1,95**	**0,26**	**0,66**	**0,73**	**0,92**	**2,95**	**1,62**	**1,44**	**0,62**	**2,41**
Uncertainty	**10,28**	**54,14**	**35,90**	**19,58**	**4,78**	**1,90**	**0,97**	**4,08**	**6,51**	**2,86**	**0,90**	**3,90**	**0,51**	**1,32**	**1,47**	**1,85**	**5,91**	**3,25**	**2,89**	**1,24**	**4,82**

Makino test piece
2000 mm/min
0,4 mm finishing

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
107	4,55	-46,14	29,51	75,65	-2,37	0,28	-1,73	4,71	-21,33	6,24	-0,08	0,19	1,06	0,79	0,00	6,56	1,68	2,70	4,92	18,73	-9,34
110	7,81	-93,16	13,94	107,10	-6,15	-0,17	-1,55	8,65	0,23	1,62	-0,18	0,15	2,31	0,81	2,28	7,98	-0,40	6,73	7,19	19,09	-13,00
125	4,43	11,77	57,20	45,43	-5,18	0,73	-3,47	6,88	-17,63	1,66	-0,17	0,19	1,30	0,37	0,20	7,09	0,64	2,38	5,74	18,60	-9,93
127	1,06	-91,04	45,79	136,83	-3,64	0,30	-1,43	6,07	-1,12	11,88	-0,10	0,31	1,55	0,65	1,41	7,79	-1,35	5,85	4,95	19,82	-12,37
Average	**4,46**	**-54,65**	**36,61**	**91,25**	**-4,33**	**0,28**	**-2,05**	**6,58**	**-9,96**	**5,35**	**-0,13**	**0,21**	**1,56**	**0,66**	**0,97**	**7,36**	**0,14**	**4,42**	**5,70**	**19,06**	**-11,16**
Deviation	**2,39**	**42,69**	**16,38**	**34,17**	**1,45**	**0,32**	**0,83**	**1,43**	**9,62**	**4,21**	**0,05**	**0,06**	**0,47**	**0,17**	**0,93**	**0,56**	**1,13**	**1,90**	**0,92**	**0,47**	**1,56**
Uncertainty	**4,77**	**85,39**	**32,75**	**68,35**	**2,89**	**0,63**	**1,66**	**2,85**	**19,24**	**8,42**	**0,09**	**0,12**	**0,94**	**0,35**	**1,85**	**1,13**	**2,27**	**3,80**	**1,84**	**0,95**	**3,11**

Daewoo test piece – Part design II
400 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
186	-20,57	111,97	80,62	-31,35	1,52	15,62	-4,36	13,64	11,63	28,29	-0,79	5,07	3,01	2,02	7,28	4,94	9,28	-7,90	7,47	-37,68	9,59
187	-22,98	161,06	125,21	-35,85	-6,47	15,52	-5,93	15,85	18,35	43,18	-1,78	8,09	2,21	3,39	13,54	1,71	14,54	-13,42	9,76	-45,63	15,16
188	-26,89	126,19	102,05	-24,14	-3,24	16,71	-2,12	15,98	7,95	36,80	-0,86	7,46	2,66	1,90	8,08	4,40	5,75	-2,81	7,46	-37,60	5,26
189	-23,77	106,43	95,71	-10,72	-2,77	15,46	-0,68	15,28	15,23	22,75	-0,51	6,88	0,31	3,00	6,57	5,30	6,54	-4,66	7,76	-43,98	8,82
Average	**-23,55**	**126,41**	**100,90**	**-25,51**	**-2,74**	**15,83**	**-3,27**	**15,19**	**13,29**	**32,76**	**-0,98**	**6,87**	**2,05**	**2,58**	**8,87**	**4,09**	**9,03**	**-7,20**	**8,11**	**-41,22**	**9,71**
Deviation	**2,26**	**21,26**	**16,05**	**9,51**	**2,84**	**0,51**	**2,02**	**0,93**	**3,89**	**7,83**	**0,48**	**1,13**	**1,04**	**0,63**	**2,75**	**1,41**	**3,44**	**4,03**	**0,96**	**3,63**	**3,55**
Uncertainty	**4,52**	**42,53**	**32,11**	**19,02**	**5,68**	**1,03**	**4,04**	**1,87**	**7,78**	**15,65**	**0,95**	**2,25**	**2,08**	**1,27**	**5,50**	**2,82**	**6,88**	**8,05**	**1,91**	**7,25**	**7,09**

Daewoo test piece – Part design II
800 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
190	-33,05	94,02	38,62	-55,40	-4,98	17,00	-2,71	17,61	5,92	33,61	-0,46	1,95	0,68	1,85	10,93	3,35	-6,76	4,84	9,00	-47,48	-2,38
191	-32,11	138,82	79,13	-59,68	-2,51	14,05	-4,58	13,78	5,75	33,93	-0,64	1,71	2,99	1,61	10,04	2,03	-1,03	0,09	8,02	-48,96	1,99
192	-20,96	75,41	36,86	-38,56	-2,25	16,29	-0,80	14,67	3,84	24,72	-0,39	1,27	0,77	2,44	9,31	3,03	-2,01	1,18	6,49	-44,27	-0,97
193	-23,28	138,16	148,72	10,56	-4,73	14,44	-1,73	15,66	4,79	26,34	-0,70	2,82	1,87	3,80	10,21	5,87	15,08	-16,42	8,59	-46,02	11,72
194	-22,17	112,72	24,47	-88,25	-1,23	16,84	-4,66	16,66	8,81	20,95	-0,46	0,21	3,06	2,69	9,15	5,96	-8,36	6,24	10,22	-46,39	-10,99
Average	**-26,32**	**111,82**	**65,56**	**-46,27**	**-3,14**	**15,72**	**-2,89**	**15,67**	**5,82**	**27,91**	**-0,53**	**1,59**	**1,87**	**2,48**	**9,93**	**4,05**	**-0,62**	**-0,81**	**8,46**	**-46,62**	**-0,13**
Deviation	**5,18**	**24,76**	**45,47**	**32,60**	**1,47**	**1,24**	**1,53**	**1,36**	**1,67**	**5,10**	**0,12**	**0,86**	**1,03**	**0,77**	**0,64**	**1,59**	**8,32**	**8,12**	**1,22**	**1,56**	**7,33**
Uncertainty	**10,35**	**49,52**	**90,94**	**65,20**	**2,93**	**2,47**	**3,07**	**2,73**	**3,34**	**10,19**	**0,24**	**1,71**	**2,06**	**1,54**	**1,29**	**3,17**	**16,64**	**16,25**	**2,45**	**3,12**	**14,66**

Statistics of test piece repeatability

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
Deviation	5,14	27,07	17,95	9,79	2,39	0,95	0,49	2,04	3,26	1,43	0,45	1,95	0,26	0,66	0,73	0,92	2,95	1,62	1,44	0,62	2,41
Deviation	2,39	42,69	16,38	34,17	1,45	0,32	0,83	1,43	9,62	4,21	0,05	0,06	0,47	0,17	0,93	0,56	1,13	1,90	0,92	0,47	1,56
Deviation	2,26	21,26	16,05	9,51	2,84	0,51	2,02	0,93	3,89	7,83	0,48	1,13	1,04	0,63	2,75	1,41	3,44	4,03	0,96	3,63	3,55
Deviation	5,18	24,76	45,47	32,60	1,47	1,24	1,53	1,36	1,67	5,10	0,12	0,86	1,03	0,77	0,64	1,59	8,32	8,12	1,22	1,56	7,33
Square sum	**4,00**	**30,08**	**27,00**	**24,58**	**2,12**	**0,84**	**1,36**	**1,49**	**5,50**	**5,17**	**0,34**	**1,21**	**0,78**	**0,60**	**1,53**	**1,19**	**4,77**	**4,70**	**1,15**	**2,01**	**4,32**
Uncertainty	**8,00**	**60,17**	**54,00**	**49,16**	**4,25**	**1,67**	**2,71**	**2,99**	**11,00**	**10,35**	**0,67**	**2,41**	**1,56**	**1,21**	**3,06**	**2,38**	**9,54**	**9,40**	**2,31**	**4,03**	**8,64**

Repeatability of CMM measurements

Long time repeatability in Sip CMM5:
Piece 2: 2000 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
107	4,55	-46,14	29,51	75,65	-2,37	0,28	-1,73	4,71	-21,33	6,24	-0,08	0,19	1,06	0,79	0,00	6,56	1,68	2,70	4,92	18,73	-9,34
125	4,43	11,77	57,20	45,43	-5,18	0,73	-3,47	6,88	-17,63	1,66	-0,17	0,19	1,30	0,37	0,20	7,09	0,64	2,38	5,74	18,60	-9,93
Average	4,49	-17,19	43,36	60,54	-3,78	0,51	-2,60	5,80	-19,48	3,95	-0,13	0,19	1,18	0,58	0,10	6,83	1,16	2,54	5,33	18,67	-9,64
Difference	0,06	28,96	13,85	15,11	1,41	0,23	0,87	1,09	1,85	2,29	0,05	0,00	0,12	0,21	0,10	0,27	0,52	0,16	0,41	0,06	0,30

Long time repeatability in Sip CMM5:
Piece 4: 2000 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
110	7,81	-93,16	13,94	107,10	-6,15	-0,17	-1,55	8,65	0,23	1,62	-0,18	0,15	2,31	0,81	2,28	7,98	-0,40	6,73	7,19	19,09	-13,00
127	1,06	-91,04	45,79	136,83	-3,64	0,30	-1,43	6,07	-1,12	11,88	-0,10	0,31	1,55	0,65	1,41	7,79	-1,35	5,85	4,95	19,82	-12,37
Average	4,43	-92,10	29,87	121,97	-4,89	0,07	-1,49	7,36	-0,44	6,75	-0,14	0,23	1,93	0,73	1,84	7,89	-0,87	6,29	6,07	19,46	-12,68
Difference	3,38	1,06	15,93	14,87	1,26	0,24	0,06	1,29	0,67	5,13	0,04	0,08	0,38	0,08	0,44	0,09	0,47	0,44	1,12	0,37	0,32

Long time repeatability in Sip CMM5:
Piece 9: 400 mm/min

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
115	-2,06	18,92	56,64	37,73	-2,27	2,39	-0,20	3,45	1,71	-4,58	0,31	3,70	3,31	0,95	7,33	4,86	-4,04	-1,17	5,35	14,02	-10,90
128	0,04	-6,10	67,68	73,77	-3,57	2,54	-2,04	3,32	-5,61	-1,83	0,10	5,64	2,49	1,00	4,53	3,44	-1,92	-3,14	4,22	14,21	-8,17
Average	-1,01	6,41	62,16	55,75	-2,92	2,47	-1,12	3,39	-1,95	-3,20	0,21	4,67	2,90	0,97	5,93	4,15	-2,98	-2,16	4,79	14,12	-9,53
Difference	1,05	12,51	5,52	18,02	0,65	0,07	0,92	0,07	3,66	1,38	0,11	0,97	0,41	0,02	1,40	0,71	1,06	0,98	0,57	0,09	1,37

Statistics of differences of long time repeatability in Sip CMM5:

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
Difference 2	0,06	28,96	13,85	15,11	1,41	0,23	0,87	1,09	1,85	2,29	0,05	0,00	0,12	0,21	0,10	0,27	0,52	0,16	0,41	0,06	0,30
Difference 4	3,38	1,06	15,93	14,87	1,26	0,24	0,06	1,29	0,67	5,13	0,04	0,08	0,38	0,08	0,44	0,09	0,47	0,44	1,12	0,37	0,32
Difference 9	1,05	12,51	5,52	18,02	0,65	0,07	0,92	0,07	3,66	1,38	0,11	0,97	0,41	0,02	1,40	0,71	1,06	0,98	0,57	0,09	1,37
Maximum	**3,38**	**28,96**	**15,93**	**18,02**	**1,41**	**0,24**	**0,92**	**1,29**	**3,66**	**5,13**	**0,11**	**0,97**	**0,41**	**0,21**	**1,40**	**0,71**	**1,06**	**0,98**	**1,12**	**0,37**	**1,37**
Deviation	**2,04**	**18,22**	**12,60**	**16,06**	**1,15**	**0,20**	**0,73**	**0,98**	**2,40**	**3,34**	**0,07**	**0,56**	**0,33**	**0,13**	**0,85**	**0,44**	**0,73**	**0,63**	**0,76**	**0,22**	**0,83**
Uncertainty	**4,09**	**36,45**	**25,19**	**32,13**	**2,31**	**0,39**	**1,46**	**1,95**	**4,80**	**6,68**	**0,15**	**1,12**	**0,66**	**0,26**	**1,70**	**0,88**	**1,47**	**1,25**	**1,53**	**0,45**	**1,66**

Short time repeatability in Zeiss UMC850S:
Piece 2: 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
141	CMM	1,72	-61,96	-4,25	57,71	-2,05	-1,52	-1,42	4,89	-16,82	13,24	-0,05	0,18	0,56	1,79	0,25	5,71	1,06	3,50	4,87	20,72	-9,82
142	CMM	1,97	-64,14	-12,68	51,46	-1,58	-0,22	-1,32	4,59	-16,68	12,29	-0,05	0,17	0,70	1,22	0,47	4,75	0,41	3,49	4,57	20,38	-10,20
143	CMM	1,79	-61,24	-11,02	50,22	-1,60	0,34	-1,02	4,46	-16,78	12,47	-0,06	0,16	0,78	0,86	0,53	4,65	1,57	2,14	4,69	20,23	-8,59
144	CMM	2,20	-61,73	-12,02	49,70	-0,78	0,02	-0,62	4,34	-15,36	12,31	-0,04	0,16	1,09	1,08	0,43	4,19	1,71	2,09	4,71	20,12	-8,51
145	CMM	2,06	-78,56	-34,05	44,51	-2,60	0,21	-4,35	4,30	-18,40	13,62	-0,11	0,12	0,62	1,31	2,25	3,52	0,03	3,56	4,48	20,12	-10,58
Average		**1,95**	**-65,53**	**-14,80**	**50,72**	**-1,72**	**-0,23**	**-1,75**	**4,51**	**-16,81**	**12,78**	**-0,06**	**0,16**	**0,75**	**1,25**	**0,79**	**4,56**	**0,95**	**2,96**	**4,66**	**20,31**	**-9,54**
Deviation		**0,17**	**6,59**	**10,08**	**4,22**	**0,60**	**0,67**	**1,33**	**0,21**	**0,96**	**0,55**	**0,03**	**0,02**	**0,19**	**0,31**	**0,74**	**0,72**	**0,65**	**0,69**	**0,13**	**0,22**	**0,84**
Uncertainty		**0,35**	**13,19**	**20,17**	**8,45**	**1,20**	**1,34**	**2,67**	**0,42**	**1,93**	**1,09**	**0,05**	**0,04**	**0,37**	**0,62**	**1,47**	**1,44**	**1,30**	**1,38**	**0,27**	**0,45**	**1,68**

Short time repeatability in Sip CMM5:
Piece 2: 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
134	CMM	1,75	-18,35	56,27	74,62	-2,55	0,53	-1,60	4,83	-14,56	8,01	-0,08	0,27	1,02	1,25	0,86	6,41	0,87	2,43	4,74	19,02	-9,36
135	CMM	2,35	-28,07	66,62	94,69	-2,53	0,96	-1,46	8,97	-10,93	8,65	-0,13	0,32	0,90	4,43	0,84	7,59	1,88	1,40	5,38	19,12	-8,01
136	CMM	2,13	-14,45	65,29	79,74	-2,49	0,56	-1,27	5,08	-15,23	9,08	-0,08	0,29	1,03	1,15	0,71	6,07	1,72	1,68	4,75	19,01	-8,29
137	CMM	2,40	-14,41	61,29	75,69	-2,80	0,37	-1,02	4,95	-15,01	8,52	-0,07	0,29	0,75	1,29	0,40	6,13	2,05	1,59	4,78	18,85	-8,06
138	CMM	2,07	-21,16	56,98	78,14	-3,07	0,38	-2,11	5,26	-14,58	10,31	-0,10	0,28	0,66	1,48	0,99	6,48	1,62	1,94	4,67	18,95	-8,58
139	CMM	1,96	-18,66	55,85	74,51	-3,20	0,66	-2,03	5,09	-13,73	9,44	-0,10	0,27	0,67	1,23	0,72	5,83	1,58	1,85	4,72	18,82	-8,54
140	CMM	2,29	-18,79	59,47	78,26	-3,36	0,50	-2,25	5,12	-16,19	8,90	-0,10	0,29	0,64	1,43	0,92	5,71	2,16	1,51	4,66	18,93	-8,00
Average		**2,14**	**-19,13**	**60,25**	**79,38**	**-2,86**	**0,57**	**-1,68**	**5,61**	**-14,32**	**8,99**	**-0,09**	**0,29**	**0,81**	**1,75**	**0,78**	**6,32**	**1,70**	**1,77**	**4,82**	**18,96**	**-8,41**
Deviation		**0,21**	**4,30**	**4,03**	**6,52**	**0,33**	**0,19**	**0,43**	**1,37**	**1,55**	**0,68**	**0,02**	**0,01**	**0,16**	**1,10**	**0,18**	**0,58**	**0,39**	**0,32**	**0,24**	**0,10**	**0,45**
Uncertainty		**0,43**	**8,59**	**8,05**	**13,03**	**0,66**	**0,37**	**0,86**	**2,75**	**3,10**	**1,36**	**0,04**	**0,03**	**0,31**	**2,20**	**0,36**	**1,16**	**0,79**	**0,64**	**0,47**	**0,20**	**0,90**

Thermal behaviour of Makino A55 milling centre

The following graphs are drawn using the temperature measured in y-axis servomotor. Temperature value is an average over 5 minutes in each measurement. Altogether 69 measurements were done and all of them are shown in graphs. The measurement itself has been a double ball bar test with Renishaw QC10, 150 millimetres radius and 2000mm/min feedrate. Equation of fitted line is evaluated using least squares fit.

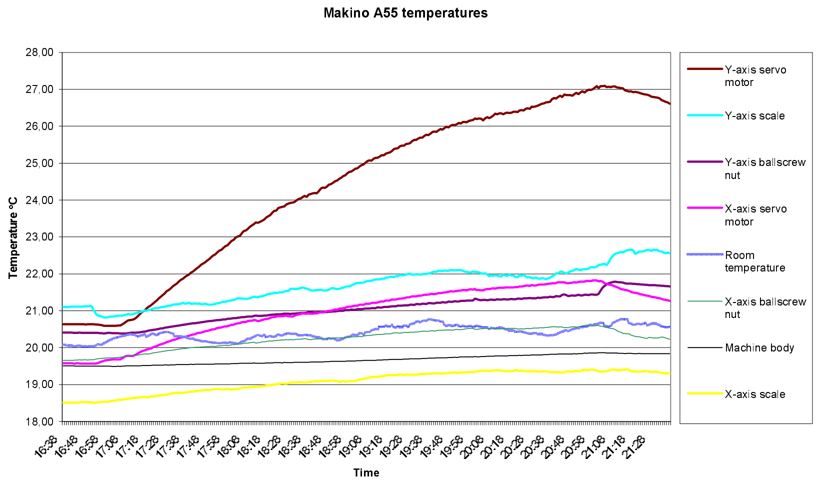


Figure 31. Temperature rise during measurements in Makino A55

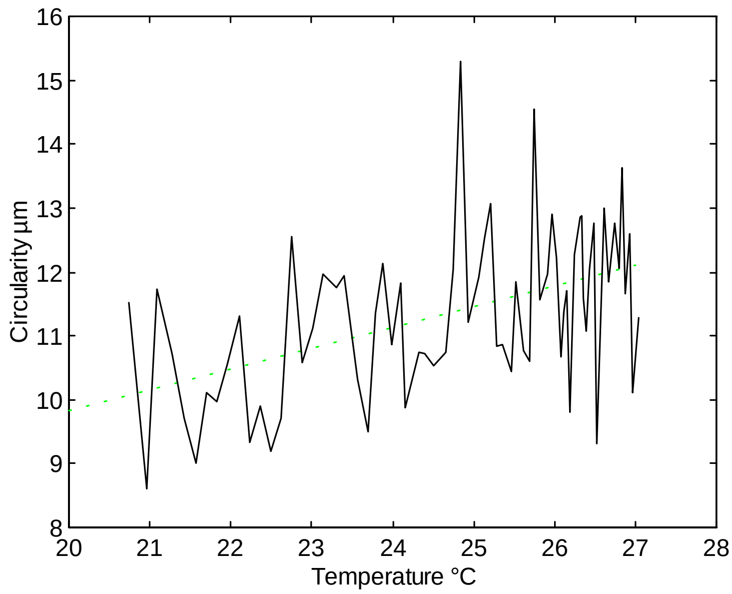


Figure 32. Circularity as a function of temperature

Fitted line: y = 0,3253 * x + 3,3303 [µm]

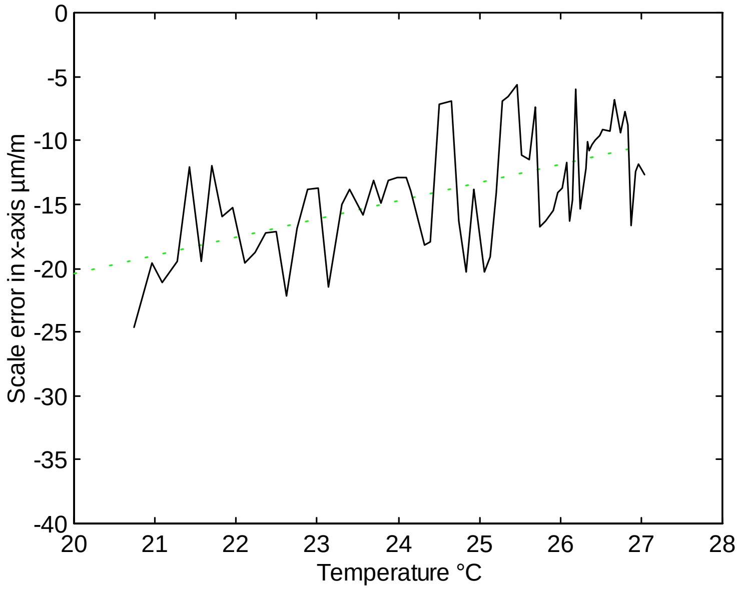


Figure 33. Scale error of x-axis as a function of temperature

Fitted line: y = 1,4217 * x – 48,8529 [µm/m]

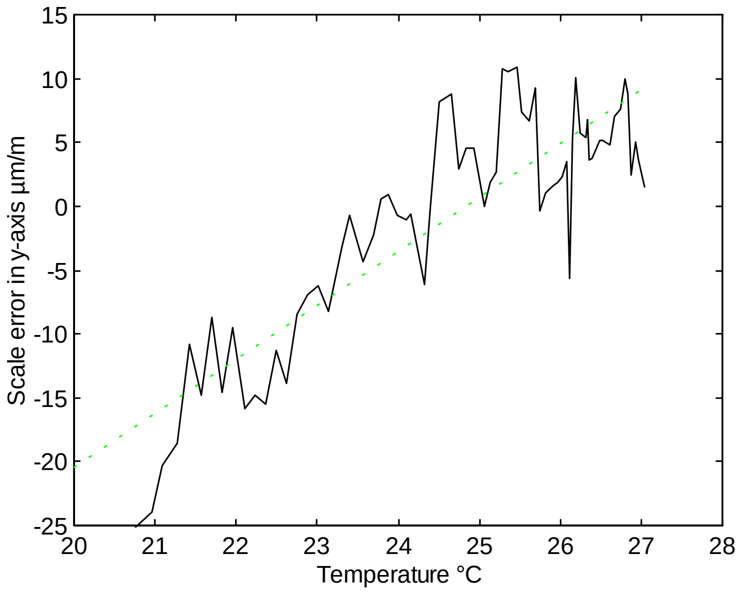


Figure 34. Scale error of y-axis as a function of temperature

Fitted line: y = 4,2231 * x – 104,8390 [µm/m]

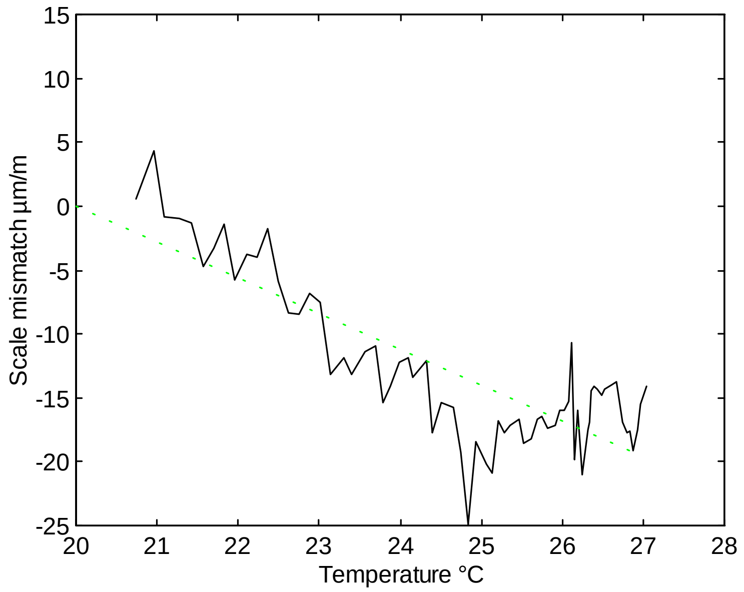


Figure 35. Scale mismatch between x- and y-axis as a function of temperature

Fitted line: y = -2,8014 * x + 55,9861 [µm/m]

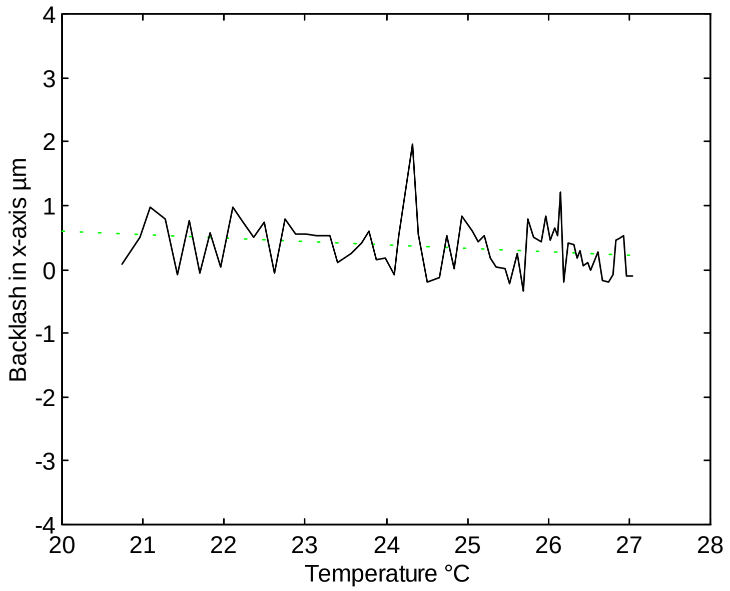


Figure 36. Backlash in x-axis as a function of temperature

Fitted line: y = -0,0509 * x + 1,6073 [µm]

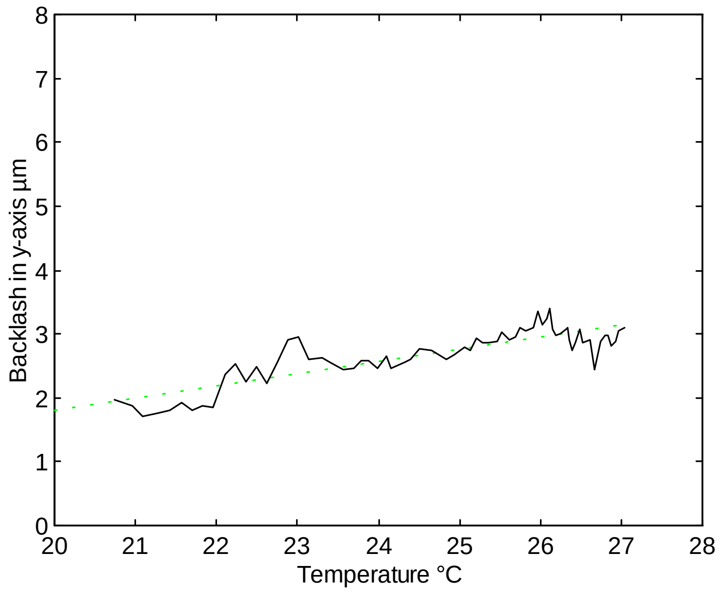


Figure 37. Backlash in y-axis as a function of temperature

Fitted line: y = 0,1893 * x - 1,9759 [µm]

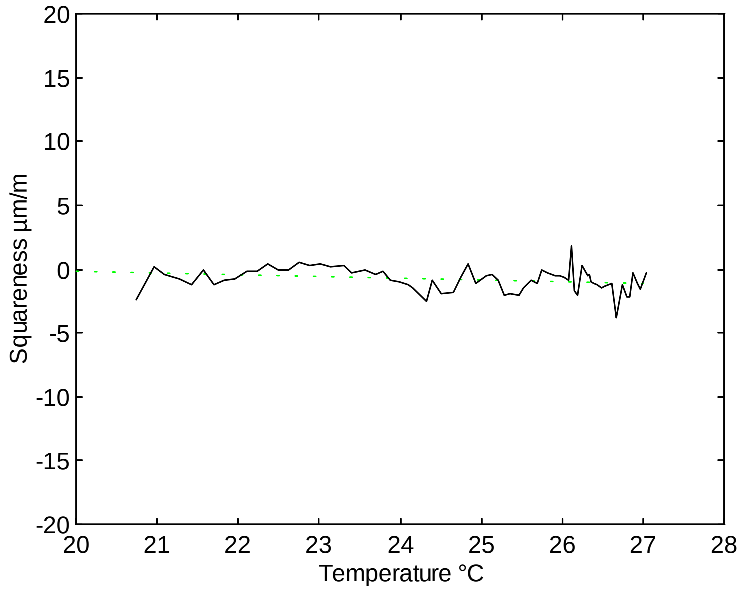


Figure 38. Squareness as a function of temperature

Fitted line: y = -0,1392 * x + 2,5969 [µm/m]

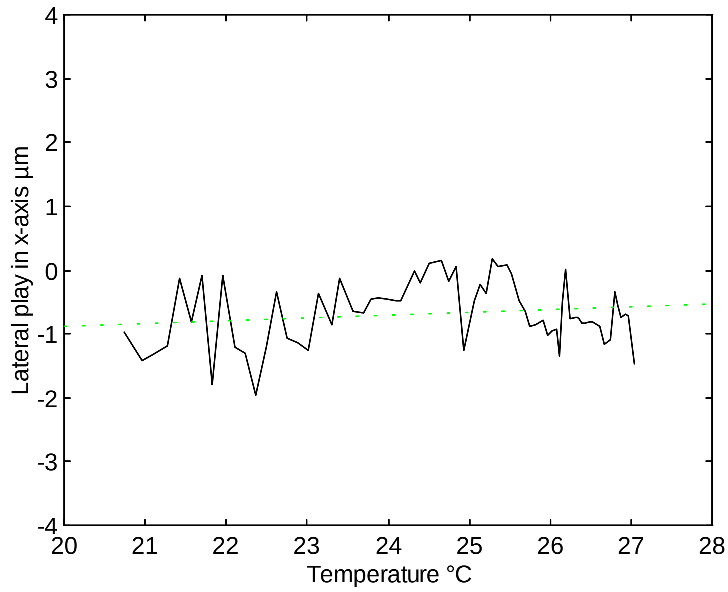


Figure 39. Lateral play in x-axis as a function of temperature

Fitted line: y = 0,0424 * x – 1,7216 [µm]

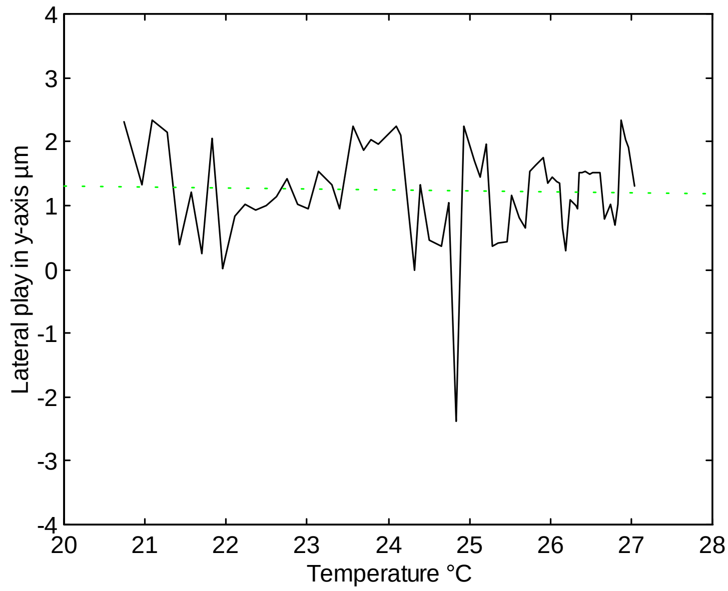


Figure 40. Lateral play in y-axis as a function of temperature

Fitted line: y = -0,0141 * x + 1,5836 [µm]

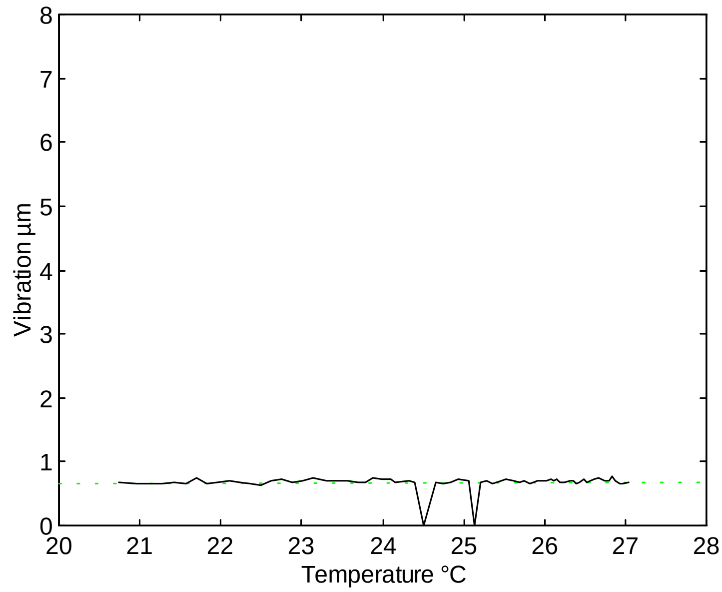


Figure 41. Vibration as a function of temperature

Fitted line: y = 0,0027 * x + 0,6080 [µm]

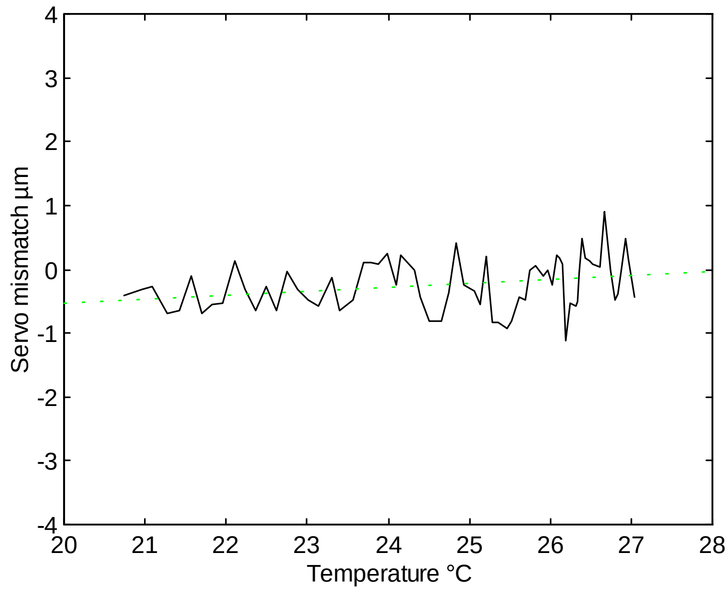


Figure 42. Servo mismatch effect as a function of temperature

Fitted line: y = 0,0606 * x – 1,7363 [µm]

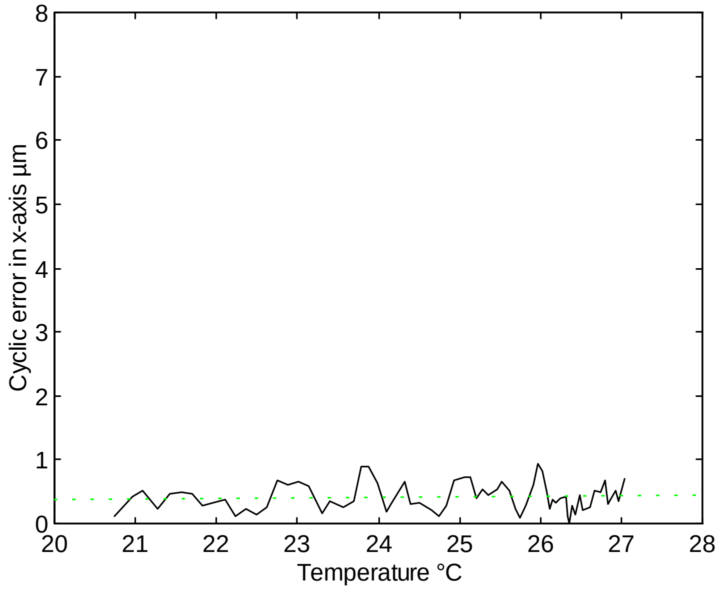


Figure 43. Cyclic error in x-axis as a function of temperature

Fitted line: y = 0,0089 * x + 0,1969 [µm]

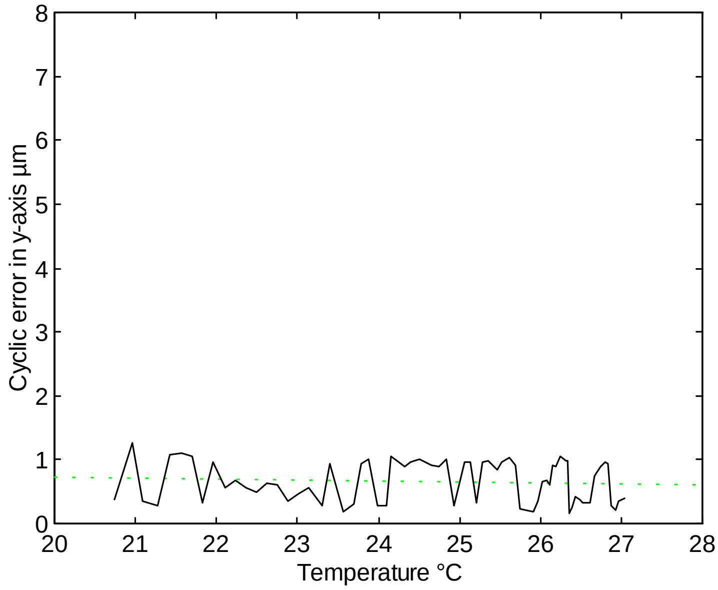


Figure 44. Cyclic error in y-axis as a function of temperature

Fitted line: y = -0,0129 * x + 0,9776 [µm]

Comparison between double ball bar analysis methods

Mitsui Seiki xy 400mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-9,65	35,7	5,5	-30,2	-3,2	0,2	2,0	1,5	14,0	-11,67	0,21		0,85	2,5	0,85	0,75	-3,75	7,75		
160	DBB	-9,75	35,36	5,43	-29,93	-3,83	0,28	2,22	1,45	12,40	-12,56	0,16	0,00	0,51	2,10	1,06	0,53	-3,96	7,62	1,25	0,00
Difference		-0,10	-0,34	-0,07	0,27	-0,63	0,08	0,22	-0,05	-1,60	-0,89	-0,05	0,00	-0,34	-0,40	0,21	-0,22	-0,21	-0,13	1,25	0,00

Mitsui Seiki xy 2000mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-10,29	38,10	-41,0	-79,1	-13,7	-3,3	-7,9	-2,0	16,67	-16,33	-0,36		1,0	2,3	1,1	0,9	-1,95	3,25		
161	DBB	-10,31	35,64	-42,40	-78,04	-13,41	-3,13	-8,56	-2,19	15,31	-16,32	-0,37	0,00	0,93	2,02	2,99	3,94	-2,14	2,99	1,81	0,00
Difference		-0,02	-2,46	-1,40	1,06	0,29	0,17	-0,66	-0,19	-1,36	0,01	-0,01	0,00	-0,07	-0,28	1,89	3,04	-0,19	-0,26	1,81	0,00

Mitsui Seiki xz 400mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-3,36	135,0	12,69	-122,4	-1,5	-3,1	0,0	0,2	15,0	-18,67	0,86		1,55	6,45	1,2	1,5	-1,55	1,35		
162	DBB	-3,37	131,50	11,76	-119,75	-1,97	-2,03	0,39	-0,84	16,67	-19,62	0,79	0,00	1,22	6,22	0,66	0,82	-1,60	1,31	3,62	0,00
Difference		-0,01	-3,50	-0,93	2,65	-0,47	1,07	0,39	-1,04	1,67	-0,95	-0,07	0,00	-0,33	-0,23	-0,54	-0,68	-0,05	-0,04	3,62	0,00

Mitsui Seiki xz 2000mm/min

ID	Device	Sqquareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-3,22	143,2	-39,4	-182,6	-14,3	-9,4	-9,5	-7,5	17,0	-27,67	0,33		1,95	6,0	0,55	0,95	-0,3	-0,1		
163	DBB	-3,22	139,95	-40,20	-180,16	-14,31	-8,65	-9,77	-8,25	18,43	-28,42	0,32	0,00	1,33	5,36	5,42	2,96	-0,36	-0,23	3,59	0,00
Difference		0,00	-3,25	-0,80	2,44	-0,01	0,75	-0,27	-0,75	1,43	-0,75	-0,01	0,00	-0,62	-0,64	4,87	2,01	-0,06	-0,13	3,59	0,00

Mitsui Seiki yz 400mm/min

ID	Device	Sqquareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	1,25	74,1	-9,5	-83,6	2,6	-0,5	3,9	-3,4	-8,67	3,33	0,65		2,4	6,45	0,25	2,55	0,05	0,4		
164	DBB	1,25	71,30	-9,35	-80,64	1,88	-2,71	4,72	-1,20	-9,86	2,16	0,62	0,00	2,65	6,13	0,75	1,24	0,13	0,52	2,47	0,00
Difference		0,00	-2,80	0,15	2,96	-0,72	-2,21	0,82	2,20	-1,19	-1,17	-0,03	0,00	0,25	-0,32	0,50	-1,31	0,08	0,12	2,47	0,00

Mitsui Seiki yz 2000mm/min

ID	Device	Sqquareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	1,51	77,3	-86,2	-163,5	-1,8	-9,3	-1,3	-10,0	-11,3	8,67	0,74		2,2	6,05	1,15	0,35	-1,0	1,55		
165	DBB	1,51	75,69	-85,57	-161,26	-2,19	-10,62	-1,23	-8,62	-12,30	7,18	0,73	0,00	2,42	6,07	2,65	1,98	-0,87	1,63	2,81	0,00
Difference		0,00	-1,61	0,63	2,24	-0,39	-1,32	0,07	1,38	-1,00	-1,49	-0,01	0,00	0,22	0,02	1,50	1,63	0,13	0,08	2,81	0,00

Statistical analysis between DBB analysis methods

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
160		-0,10	-0,34	-0,07	0,27	-0,63	0,08	0,22	-0,05	-1,60	-0,89	-0,05		-0,34	-0,40	0,21	-0,22	-0,21	-0,13		
161		-0,02	-2,46	-1,40	1,06	0,29	0,17	-0,66	-0,19	-1,36	0,01	-0,01		-0,07	-0,28	1,89	3,04	-0,19	-0,26		
162		-0,01	-3,50	-0,93	2,65	-0,47	1,07	0,39	-1,04	1,67	-0,95	-0,07		-0,33	-0,23	-0,54	-0,68	-0,05	-0,04		
163		0,00	-3,25	-0,80	2,44	-0,01	0,75	-0,27	-0,75	1,43	-0,75	-0,01		-0,62	-0,64	4,87	2,01	-0,06	-0,13		
164		0,00	-2,80	0,15	2,96	-0,72	-2,21	0,82	2,20	-1,19	-1,17	-0,03		0,25	-0,32	0,50	-1,31	0,08	0,12		
165		0,00	-1,61	0,63	2,24	-0,39	-1,32	0,07	1,38	-1,00	-1,49	-0,01		0,22	0,02	1,50	1,63	0,13	0,08		
Average		-0,02	-2,33	-0,40	1,94	-0,32	-0,24	0,09	0,26	-0,34	-0,87	-0,03		-0,15	-0,31	1,41	0,74	-0,05	-0,06		
Squared sum		0,04	2,56	0,81	2,16	0,48	1,18	0,48	1,19	1,39	0,99	0,04		0,35	0,36	2,24	1,74	0,14	0,14		
Uncertainty		0,08	5,12	1,62	4,32	0,96	2,36	0,96	2,37	2,79	1,97	0,08		0,69	0,73	4,49	3,48	0,27	0,28		

Comparison between cross grid encoder and double ball bar measurements

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
60	-1,54	-3,02	68,03	71,05	-0,07	-0,29	0,97	-1,63	-6,48	-4,73	0,06		-0,88	0,47	1,43	2,51	0,18	-0,72			
61	-2,13	-5,31	72,34	77,64	-0,11	-0,03	1,01	-1,21	-6,11	-4,49	0,06		-0,93	0,46	1,36	2,74	0,08	-0,71			
62	-1,59	-7,10	61,59	68,70	-0,24	-0,31	0,86	-1,33	-7,25	-7,63	0,23		-0,56	0,27	0,64	1,19	0,60	-0,87			
63	-2,07	-7,75	65,12	72,87	-0,41	-0,23	0,77	-1,21	-7,43	-7,20	0,22		-0,53	0,17	0,82	1,02	0,62	-0,86			
65	-1,43	-26,13	40,41	66,54	-0,79	-1,62	0,64	-1,22	3,42	-4,54	0,05		-0,88	0,10	1,36	1,69	-0,07	0,22			
66	-1,49	-26,64	39,60	66,25	-0,68	-1,69	0,40	-1,21	3,63	-4,59	0,06		-0,88	0,14	2,22	2,49	-0,05	0,17			
67	-1,91	-26,17	29,59	55,76	-0,71	-1,68	0,21	-1,05	3,35	-4,46	0,17		-0,82	0,19	0,62	0,85	0,36	-0,48			
68	-1,80	-24,04	29,73	53,77	-0,83	-1,21	0,08	-1,16	3,34	-4,61	0,13		-0,51	0,57	0,59	0,74	0,29	-0,48			
69	0,47	1,76	60,73	58,97	3,28	0,61	-1,60	-1,41	-10,32	25,40	0,00		0,78	0,07	4,12	3,49	0,10	-1,08			
70	-1,04	0,67	62,10	61,42	2,23	-0,02	-1,08	-0,35	-7,01	21,00	0,01		0,48	-0,47	3,59	2,05	-0,05	-0,81			
71	-1,93	0,45	48,08	47,63	1,72	-0,52	-0,41	-1,36	-2,23	25,36	0,24		-0,17	0,04	2,41	0,61	1,03	-1,38			
72	-2,06	-0,80	47,42	48,22	1,72	-0,48	-0,55	-1,32	-2,50	25,96	0,23		-0,24	0,03	2,39	0,61	1,07	-1,39			
85	-0,33	-45,55	37,37	82,91	1,45	1,38	1,30	-3,76	4,03	4,21	0,72		-0,29	-0,71	0,10	3,00	-0,08	-0,91			
86	0,88	-56,87	63,33	120,20	2,15	3,29	1,49	-0,02	0,74	4,00	0,08		-0,20	0,28	6,66	6,37	-0,03	-0,88			
87	-4,69	-15,39	22,07	37,46	-0,05	-0,76	-2,38	0,78	3,90	9,96	-0,12		-0,14	1,47	1,78	4,35	-1,51	-3,11			
88	-4,55	15,47	47,57	68,23	-1,21	-0,02	0,08	3,25	7,09	10,00	-0,05		0,48	0,97	11,01	15,30	-0,26	-1,45			
89	-2,83	15,82	58,41	42,59	-2,32	0,33	-3,38	-0,97	-0,34	15,39	-0,30		-0,86	0,95	4,92	4,70	0,84	-1,09			
90	-2,92	23,97	107,89	83,93	-1,63	1,98	-1,66	1,08	-3,14	7,04	-0,08		0,13	0,68	7,05	15,20	0,53	-1,39			
91	-4,41	-2,47	31,60	34,06	-2,46	-1,25	-0,24	-1,04	1,11	-8,24	0,01		0,29	-0,37	1,27	1,15	1,91	-0,82			
92	-3,72	-7,75	33,88	41,63	-2,46	-1,12	0,06	-0,02	-4,98	2,78	0,01		0,38	-0,24	2,52	1,47	2,02	-1,16			
93	-4,60	-26,91	-5,45	21,46	-0,63	-1,49	-3,08	-1,89	-14,51	-0,91	0,19		0,67	-0,73	2,54	0,98	1,59	3,96			
94	-9,88	-23,51	-3,19	20,31	-3,68	-1,48	-3,41	1,18	10,33	3,41	0,03		-0,06	-1,08	4,71	0,88	-1,18	1,01			
95	-16,17	135,21	163,38	28,17	-2,86	2,11	14,57	2,44	-1,08	40,39	-0,25		2,12	0,27	14,08	1,02	3,02	-0,87			
96	9,91	164,70	217,7	53,00	-3,43	6,31	5,62	-4,42	27,5	24,95	0,27		0,72	0,88	10,22	5,16	1,51	5,04			
116	5,63	-32,00	12,61	44,6	-1,72	0,89	-0,18	0,08	-4,11	-5,15	-0,17		0,11	0,31	1,56	-0,49	1,11	-0,98			
117	6,87	-19,73	35,13	54,86	-2,00	-0,33	-1,52	1,69	-11,15	-4,91	-0,05		0,30	0,02	8,28	3,46	0,21	-0,95			
119	-1,01	-32,77	33,13	65,9	-1,53	-1,91	-0,60	-0,27	0,51	-0,49	-0,06		-0,29	-0,31	0,93	0,86	3,53	-1,58			
121	-1,28	-23,23	38,19	61,42	-1,68	-1,52	-2,00	0,03	-1,00	3,07	-0,02		-0,13	-0,22	8,30	5,98	0,12	-0,78			
122	2,07	26,27	54,52	28,25	-1,44	-0,34	-1,30	-0,87	2,17	1,82	-0,22		-0,33	-0,20	1,19	0,30	0,55	-1,13			
123	2,37	24,65	64,48	39,83	-0,97	-0,15	-1,11	-0,71	0,37	3,58	-0,02		0,14	-0,24	2,48	7,97	0,01	-0,32			
146	-1,29	-25,65	71,15	96,80	-3,81	-1,56	-10,52	-0,47	-9,67	7,88	-0,49		0,53	-2,23	2,55	1,46	2,66	-1,48			
147	-1,71	-39,54	119,29	158,84	-0,69	-0,54	-6,95	-1,61	-4,26	-6,72	-0,04		0,08	-1,39	12,19	5,92	0,51	-0,47			
148	-6,47	-40,11	59,32	99,53	-3,64	-3,94	-2,92	-10,64	-13,12	9,57	-0,10		0,38	-2,22	1,59	12,18	3,71	2,29			

149	-4,47	-42,39	127,26	169,65	1,53	-1,54	-2,47	-7,28	-1,05	0,9	0,05		-1,05	-1,10	11,30	2,29	2,66	1,84			
150	4,29	15,69	73,95	58,26	-2,84	-7,25	-0,81	-7,35	10,82	-545	0,27		0,84	-4,38	1,61	1,45	-2,74	-1,01			
151	1,95	21,91	155,42	133,5	-2,06	-2,40	-0,76	-4,74	9,28	-6,05	0,01		1,22	-4,27	12,30	3,00	-1,31	-2,27			
174	3,62	-43,1	112,48	155,54	-2,04	-5,67	-1,76	-3,07	4,18	-6,7	0,30		0,35	0,07	4,55	5,20	-0,05	0,35			
175	2,82	-59,6	209,12	-35,8	-0,86	-4,24	2,0	-6,5	-3,30	-5,76	0,19		0,78	2,60	10,58	5,30	-0,89	-0,65			
176	3,49	11,15	128,88	117,72	-3,37	-5,42	-1,32	-7,81	13,45	-12,83	0,77		0,40	1,94	2,31	7,02	-2,84	-1,99			
177	2,96	-25,35	144,36	169,71	-0,13	0,37	-2,04	-12,17	6,05	-1,82	0,08		-0,24	-0,22	4,75	2,96	-3,51	-1,23			
178	-6,40	297,04	383,68	86,64	-3,61	-3,70	-3,70	-1,01	11,51	-42,80	-1,09		0,80	3,12	4,06	8,30	3,39	1,51			
179	-9,86	92,0	307,59	215,59	4,46	-3,16	-6,87	1,48	25,69	-1,09	-0,36		4,68	2,71	5,92	4,07	5,44	3,04			
Average	**-1,39**	**3,76**	**84,04**	**73,90**	**-0,91**	**-0,97**	**-0,82**	**-1,88**	**0,75**	**-10,57**	**0,02**		**0,16**	**-0,04**	**4,40**	**3,73**	**0,60**	**-0,38**			
Squared sum	**4,80**	**63,57**	**114,41**	**87,76**	**2,15**	**2,53**	**3,64**	**3,75**	**8,82**	**85,21**	**0,29**		**0,98**	**1,44**	**5,85**	**5,22**	**1,85**	**1,63**			
Uncertainty	**9,59**	**127,14**	**228,83**	**175,53**	**4,29**	**5,06**	**7,27**	**7,50**	**17,64**	**170,41**	**0,58**		**1,95**	**2,89**	**11,69**	**10,44**	**3,69**	**3,25**			

Comparison between test piece and double ball bar measurements

ID	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
106 Diff.	-2,94	1,16	92,70	91,54	-1,31	-2,36	-0,21	-2,71	-8,77	-5,80	0,59		0,55	0,07	2,85	3,34	-3,42	-0,43			
107 Diff.	4,90	-50,94	86,21	137,15	-2,57	-1,62	-1,63	1,41	-24,33	2,57	-0,04		0,11	0,49	0,00	5,76	1,88	1,75			
109 Diff.	-2,32	12,61	106,91	94,30	-1,24	-1,57	0,34	-1,99	-10,03	-5,54	0,57		0,63	-0,48	3,43	2,46	-4,48	0,70			
110 Diff.	4,78	6,97	113,90	106,93	-5,38	-1,17	-3,37	3,58	-20,63	-2,01	-0,13		0,35	0,07	0,20	6,29	0,84	1,43			
112 Diff.	8,50	-39,58	72,80	112,39	-5,54	-1,26	-0,21	0,39	-1,55	-2,46	-0,16		1,09	1,33	2,77	4,17	-0,89	-0,09			
114 Diff.	6,61	-52,21	60,22	112,42	-6,47	0,26	-1,02	2,46	-7,63	-3,29	-0,44		1,11	0,15	1,43	4,94	3,19	-3,56			
126 Diff.	3,74	19,03	24,6	5,57	-5,95	-0,64	-2,18	1,01	-12	3,16	-0,79		0,3	-0,33	2,89	7,89	2,76	0,33			
158 Diff.	-2,07	18,80	28,50	9,70	-8,77	-6,26	-14,48	0,26	-14,70	7,57	-1,09		0,26	-1,52	4,64	7,06	2,96	-1,50			
189 Diff.	-6,34	62,33	86,01	23,68	-4,67	5,56	-3,18	2,78	6,90	23,75	-0,65		-0,54	1,50	6,57	4,65	6,59	-12,26			
Average	**1,65**	**-2,43**	**74,65**	**77,08**	**-4,66**	**-1,01**	**-2,88**	**0,80**	**-10,30**	**1,99**	**-0,24**		**0,43**	**0,14**	**2,75**	**5,17**	**1,05**	**-1,51**			
Squared sum	**5,11**	**36,05**	**80,39**	**90,35**	**5,22**	**3,06**	**5,16**	**2,14**	**13,59**	**8,96**	**0,59**		**0,64**	**0,88**	**3,38**	**5,43**	**3,44**	**4,36**			
Uncertainty	**10,23**	**72,10**	**160,79**	**180,70**	**10,45**	**6,12**	**10,32**	**4,28**	**27,19**	**17,93**	**1,18**		**1,28**	**1,76**	**6,76**	**10,86**	**6,89**	**8,72**			

Comparison between test piece and cross grid encoder measurements

Daewoo xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
85	Grid	-18,21	-7,47	31,39	38,86	1,45	10,60	2,74	8,25	14,45	3,41	0,69	4,77	0,70	0,70	1,33	3,56	0,01	7,39	3,66		
189	CMM	-23,77	106,43	95,71	-10,72	-2,77	15,46	-0,68	15,28	15,23	22,75	-0,51	6,88	0,31	3,00	6,57	5,30	6,54	-4,66	7,76	-43,98	8,82
Difference		**- 5,56**	**113,90**	**64,32**	**- 49,58**	**- 4,22**	**4,86**	**- 3,42**	**7,03**	**0,78**	**19,34**	**- 1,20**	**2,11**	**- 0,39**	**2,30**	**5,24**	**1,74**	**6,53**	**- 12,05**	**4,10**		

Daewoo xy 800 mm/min (Test piece 800mm/min and cross grid 400mm/min)

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
85	Grid	-18,21	-7,47	31,39	38,86	1,45	10,60	2,74	8,25	14,45	3,41	0,69	4,77	0,70	0,70	1,33	3,56	0,01	7,39	3,66		
190	CMM	-33,05	94,02	38,62	-55,40	-4,98	17,00	-2,71	17,61	5,92	33,61	-0,46	1,95	0,68	1,85	10,93	3,35	-6,76	4,84	9,00	-47,48	-2,38
Difference		**- 14,84**	**101,49**	**7,23**	**- 94,26**	**- 6,43**	**6,40**	**- 5,45**	**9,36**	**- 8,53**	**30,20**	**- 1,15**	**- 2,82**	**- 0,02**	**1,15**	**9,60**	**- 0,21**	**- 6,77**	**- 2,55**	**5,34**		

Makino A55 xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
62	Grid	-1,98	-2,66	13,29	15,96	0,03	1,97	0,69	2,08	-4,39	-2,54	0,10	1,57	0,30	0,97	0,76	1,19	-0,08	0,34	1,20		
109	CMM	-2,67	18,01	60,01	42,00	-0,74	0,73	0,34	1,41	-7,36	-0,54	0,48	4,12	1,48	0,17	3,43	2,46	-5,18	1,85	3,13	14,33	-11,55
Difference		**- 0,69**	**20,67**	**46,72**	**26,04**	**- 0,77**	**- 1,24**	**- 0,35**	**- 0,67**	**- 2,97**	**2,00**	**0,38**	**2,55**	**1,18**	**- 0,80**	**2,67**	**1,27**	**- 5,10**	**1,51**	**1,93**		

Makino A55 xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
60	Grid	-1,89	1,76	10,45	8,69	0,33	1,50	0,89	1,62	-3,45	-0,82	0,02	0,35	0,08	0,77	1,32	3,34	0,03	0,34	3,74		
110	CMM	4,43	11,77	57,20	45,43	-5,18	0,73	-3,47	6,88	-17,63	1,66	-0,17	0,19	1,30	0,37	0,20	7,09	0,64	2,38	5,74	18,60	-9,93
Difference		**6,32**	**10,01**	**46,75**	**36,74**	**- 5,51**	**- 0,77**	**- 4,36**	**5,26**	**- 14,18**	**2,48**	**- 0,19**	**- 0,16**	**1,22**	**- 0,40**	**- 1,12**	**3,75**	**0,61**	**2,04**	**2,00**		

Makino A77 xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
91	Grid	-3,07	-5,89	45,85	51,75	1,44	0,33	1,75	1,05	2,42	-3,25	0,07	0,72	1,09	0,72	1,27	1,15	-0,45	0,18	1,48		
126	CMM	5,08	15,63	38,90	23,27	-2,05	0,96	-0,18	3,11	-10,70	8,16	-0,73	0,79	1,10	0,77	2,89	7,89	0,41	1,33	5,33	30,08	-6,14
Difference		**8,15**	**21,52**	**- 6,95**	**- 28,48**	**- 3,49**	**0,63**	**- 1,93**	**2,06**	**- 13,12**	**11,41**	**- 0,80**	**0,07**	**0,01**	**0,05**	**1,62**	**6,74**	**0,86**	**1,15**	**3,85**		

Mitsui Seiki xy 400mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
146	Grid	-10,94	10,04	76,66	66,62	-7,01	-1,35	-8,52	1,03	4,32	-3,79	-0,28	2,25	1,38	0,27	3,40	2,21	-1,09	6,27	3,31		
158	CMM	-11,72	54,50	34,00	-20,50	-11,97	-6,06	-12,48	1,76	-0,70	-4,10	-0,88	-0,51	1,11	0,98	5,49	7,81	-0,79	6,25	6,67	12,22	-4,94
Difference		**- 0,78**	**44,46**	**- 42,66**	**- 87,12**	**- 4,96**	**- 4,71**	**- 3,96**	**0,73**	**- 5,02**	**- 0,31**	**- 0,60**	**- 2,76**	**- 0,27**	**0,71**	**2,09**	**5,60**	**0,30**	**- 0,02**	**3,36**		

Statistics of comparison between test piece and cross grid encoder measurements

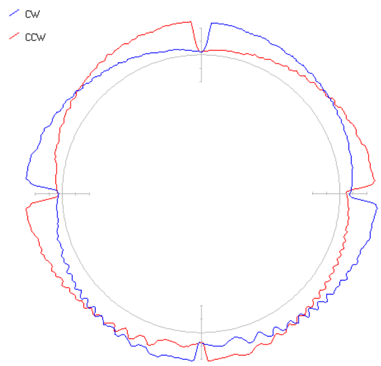
ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
Daewoo 400		-5,56	113,90	64,32	-49,58	-4,22	4,86	-3,42	7,03	0,78	19,34	-1,20	2,11	-0,39	2,30	5,24	1,74	6,53	-12,05	4,10		
A55 400		-0,69	20,67	46,72	26,04	-0,77	-1,24	-0,35	-0,67	-2,97	2,00	0,38	2,55	1,18	-0,80	2,67	1,27	-5,10	1,51	1,93		
A55 2000		6,32	10,01	46,75	36,74	-5,51	-0,77	-4,36	5,26	-14,18	2,48	-0,19	-0,16	1,22	-0,40	-1,12	3,75	0,61	2,04	2,00		
A77 400		8,15	21,52	-6,95	-28,48	-3,49	0,63	-1,93	2,06	-13,12	11,41	-0,80	0,07	0,01	0,05	1,62	6,74	0,86	1,15	3,85		
Mitsui 400		-0,78	44,46	-42,66	-87,12	-4,96	-4,71	-3,96	0,73	-5,02	-0,31	-0,60	-2,76	-0,27	0,71	2,09	5,60	0,30	-0,02	3,36		
Average		**1,49**	**42,11**	**21,64**	**-20,48**	**-3,79**	**-0,25**	**-2,80**	**2,88**	**-6,90**	**6,98**	**-0,48**	**0,36**	**0,35**	**0,37**	**2,10**	**3,82**	**0,64**	**-1,47**	**3,05**		
Squared sum		**5,26**	**56,46**	**45,55**	**50,77**	**4,14**	**3,11**	**3,17**	**4,06**	**9,03**	**10,14**	**0,72**	**1,93**	**0,79**	**1,15**	**2,93**	**4,37**	**3,74**	**5,53**	**3,18**		
Uncertainty		**10,52**	**112,93**	**91,10**	**101,54**	**8,27**	**6,22**	**6,34**	**8,11**	**18,06**	**20,29**	**1,45**	**3,86**	**1,58**	**2,30**	**5,85**	**8,74**	**7,48**	**11,06**	**6,37**		

Compensation case of a xy-table

A xy-table was used as a compensation case for the feature based machine tool analysis. This machine has only two axis x and y, which are driven by trapeze screws. The encoders are mounted at the end of digital servo motors. A Siemens 840D PC-based numerical controller is used to control this quite an old machine. The table has considerable geometrical deviations, but the repeatability, at least for circles, is sufficient. The new controller on the other hand offers a wide variety of compensation possibilities.

Before compensations

When all compensations were set to zero the circularity value for the xy-table proved to be around 140µm. The first measurement was done by DBB and analysed by the FeatureCheck software. The major source of deviations was backlash on both axes.

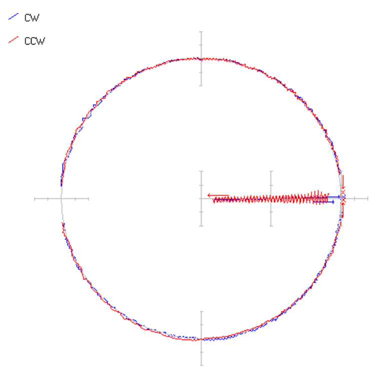


Deviation type	X-axis	Y-axis
Circularity	137 µm	
Axis spike	0 µm	0 µm
Backlash	99 µm	81 µm
Cyclic error	12 µm	11 µm
Lateral play	-3 µm	-4 µm
Scale error	805 µm	711 µm
Servo mismatch	12,5 µm	
Squareness	218 $^{\mu m}/_{m}$	
Straightness	12 $^{\mu m}/_{200mm}$	-15 $^{\mu m}/_{200mm}$

Figure 45. Xy-table before compensations (50µm/div)

After compensations

The deviation values obtained from the first measurement were used to compensate the machine tool. After the first compensation a second test was needed to adjust the compensation values. The last measurement was accomplished using the cross grid encoder and the achieved circularity was 19µm.



Deviation type	X-axis	Y-axis
Circularity	19 µm	
Axis spike	5 µm	4 µm
Backlash	-2 µm	-2 µm
Cyclic error	0 µm	4 µm
Lateral play	1 µm	2 µm
Scale error	49 $^{\mu m}/_{m}$	20 $^{\mu m}/_{m}$
Servo mismatch	-1,0 µm	
Squareness	1 $^{\mu m}/_{m}$	
Straightness	6 $^{\mu m}/_{140mm}$	-3 $^{\mu m}/_{140mm}$

Figure 46. Xy-table after compensations (50µm/div)

Measurements of Daewoo ACE-H50X

Daewoo xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
85	Grid	-17,76	-1,45	47,07	48,51	3,35	11,28	3,80	8,74	12,36	3,21	0,86	6,18	0,56	0,79	0,10	3,65	-0,13	6,69	0,23		
Difference		**-0,33**	**-45,55**	**37,37**	**82,91**	**1,45**	**1,38**	**1,30**	**-3,76**	**4,03**	**4,21**	**0,72**		**-0,29**	**-0,71**	**0,10**	**3,00**	**-0,08**	**-0,91**			

Daewoo xy 400 mm/min – Part design I – No upmilling

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
97	CMM	-20,37	21,11	118,03	96,91	6,68	0,17	2,26	0,86	11,87	32,58	1,76	10,64	6,47	2,32	10,10	8,20	0,51	-0,08	1,22	-36,94	
100	CMM	-22,85	57,46	143,67	86,21	11,81	-5,05	6,42	-2,00	18,95	47,30	2,62	12,82	5,26	3,94	8,04	6,07	2,27	-1,58	1,90	-45,01	
130	CMM	-23,60	14,79	147,88	133,09	11,37	1,40	3,24	2,93	10,99	25,63	2,31	13,22	2,63	1,58	7,06	7,72	-1,96	2,07	1,70	-43,30	
131	CMM	-26,77	24,89	141,77	116,89	10,28	1,30	5,04	0,91	5,44	39,80	2,39	13,35	5,22	1,17	8,26	8,26	0,33	0,12	1,60	-37,00	
CMM average		-23,40	29,56	137,84	108,28	10,03	-0,55	4,24	0,68	11,81	36,33	2,27	12,51	4,89	2,25	8,37	7,56	0,29	0,13	1,61	-40,56	
97	Diff.	-2,94	-22,99	108,33	131,31	4,78	-9,73	-0,24	-11,64	3,54	33,58	1,62		5,62	0,82	10,10	7,55	0,56	-7,68			
100	Diff.	-5,42	13,36	133,97	120,61	9,91	-14,95	3,92	-14,50	10,62	48,30	2,48		4,41	2,44	8,04	5,42	2,32	-9,18			
130	Diff.	-6,17	-29,31	138,18	167,49	9,47	-8,50	0,74	-9,57	2,66	26,63	2,17		1,78	0,08	7,06	7,07	-1,91	-5,53			
131	Diff.	-9,34	-19,21	132,07	151,29	8,38	-8,60	2,54	-11,59	-2,89	40,80	2,25		4,37	-0,33	8,26	7,61	0,38	-7,48			
Difference		**-5,97**	**-14,54**	**128,14**	**142,68**	**8,13**	**-10,45**	**1,74**	**-11,82**	**3,48**	**37,33**	**2,13**		**4,04**	**0,75**	**8,37**	**6,91**	**0,34**	**-7,47**			

Daewoo xy 400 mm/min – Part design I

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
97	CMM	-20,44	18,79	117,01	98,23	6,35	1,22	1,26	1,21	11,63	32,53	1,58	10,65	6,40	2,25	10,19	8,20	8,58	-8,14	9,50	-36,94	9,30
100	CMM	-22,99	56,11	143,06	86,96	11,61	-4,43	5,84	-1,81	18,69	47,23	2,52	12,83	5,23	3,91	8,65	6,13	7,10	-6,41	11,10	-45,01	5,56
130	CMM	-23,67	12,59	146,91	134,32	11,06	2,42	2,35	3,26	10,73	25,59	2,15	13,23	2,56	1,56	7,23	7,73	5,53	-5,45	8,47	-43,29	8,65
131	CMM	-26,81	24,40	141,55	117,15	10,21	1,52	4,87	0,99	5,36	39,80	2,36	13,35	5,20	1,17	8,30	8,26	2,01	-1,56	8,75	-37,00	1,93
CMM average		-23,48	27,97	137,13	109,16	9,81	0,18	3,58	0,91	11,60	36,29	2,15	12,52	4,85	2,22	8,59	7,58	5,81	-5,39	9,45	-40,56	6,36
97	Diff.	-3,01	-25,31	107,31	132,63	4,45	-8,68	-1,24	-11,29	3,30	33,53	1,44		5,55	0,75	10,19	7,55	8,63	-15,74			
100	Diff.	-5,56	12,01	133,36	121,36	9,71	-14,33	3,34	-14,31	10,36	48,23	2,38		4,38	2,41	8,65	5,48	7,15	-14,01			
130	Diff.	-6,24	-31,51	137,21	168,72	9,16	-7,48	-0,15	-9,24	2,40	26,59	2,01		1,71	0,06	7,23	7,08	5,58	-13,05			
131	Diff.	-9,38	-19,70	131,85	151,55	8,31	-8,38	2,37	-11,51	-2,97	40,80	2,22		4,35	-0,33	8,30	7,61	2,06	-9,16			
Difference		**-6,05**	**-16,13**	**127,43**	**143,56**	**7,91**	**-9,72**	**1,08**	**-11,59**	**3,27**	**37,29**	**2,01**		**4,00**	**0,72**	**8,59**	**6,93**	**5,86**	**-12,99**			

Daewoo xy 400 mm/min – Part design II

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
186	CMM	-20,57	111,97	80,62	-31,35	1,52	15,62	-4,36	13,64	11,63	28,29	-0,79	5,07	3,01	2,02	7,28	4,94	9,28	-7,90	7,47	-37,68	9,59
187	CMM	-22,98	161,06	125,21	-35,85	-6,47	15,52	-5,93	15,85	18,35	43,18	-1,78	8,09	2,21	3,39	13,54	1,71	14,54	-13,42	9,76	-45,63	15,16
188	CMM	-26,89	126,19	102,05	-24,14	-3,24	16,71	-2,12	15,98	7,95	36,80	-0,86	7,46	2,66	1,90	8,08	4,40	5,75	-2,81	7,46	-37,60	5,26
189	CMM	-23,77	106,43	95,71	-10,72	-2,77	15,46	-0,68	15,28	15,23	22,75	-0,51	6,88	0,31	3,00	6,57	5,30	6,54	-4,66	7,76	-43,98	8,82
CMM average		-23,55	126,41	100,90	-25,51	-2,74	15,83	-3,27	15,19	13,29	32,76	-0,98	6,87	2,05	2,58	8,87	4,09	9,03	-7,20	8,11	-41,22	9,71
186	Diff.	-3,14	67,87	70,92	3,05	-0,38	5,72	-6,86	1,14	3,30	29,29	-0,93		2,16	0,52	7,28	4,29	9,33	-15,50			
187	Diff.	-5,55	116,96	115,51	-1,45	-8,37	5,62	-8,43	3,35	10,02	44,18	-1,92		1,36	1,89	13,54	1,06	14,59	-21,02			
188	Diff.	-9,46	82,09	92,35	10,26	-5,14	6,81	-4,62	3,48	-0,38	37,80	-1,00		1,81	0,40	8,08	3,75	5,80	-10,41			
189	Diff.	-6,34	62,33	86,01	23,68	-4,67	5,56	-3,18	2,78	6,90	23,75	-0,65		-0,54	1,50	6,57	4,65	6,59	-12,26			
Difference		**-6,12**	**82,31**	**91,20**	**8,89**	**-4,64**	**5,93**	**-5,77**	**2,69**	**4,96**	**33,76**	**-1,12**		**1,20**	**1,08**	**8,87**	**3,44**	**9,08**	**-14,80**			

Daewoo xy 800 mm/min (Test piece 800mm/min and DBB 400mm/min) – Part design I - No upmilling

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
103	CMM	-32,87	-13,32	73,97	87,29	10,29	1,71	1,42	-1,00	7,33	36,43	1,23	3,46	1,93	2,03	11,15	8,24	-5,20	2,10	2,18	-46,66	
105	CMM	-32,08	51,55	96,03	44,48	7,03	-0,11	0,89	-2,64	7,40	37,17	0,81	2,74	5,52	2,35	11,14	7,14	-2,71	1,61	3,15	-48,47	
129	CMM	-20,89	-12,20	87,18	99,38	11,02	0,90	3,07	1,48	0,56	27,60	1,06	2,78	2,78	1,59	9,40	6,67	-1,62	-0,80	2,14	-43,67	
132	CMM	-22,08	-13,46	45,25	58,71	6,39	3,85	-3,32	2,66	4,65	24,39	0,69	1,56	5,83	1,93	12,26	8,82	0,57	-2,72	1,66	-45,94	
133	CMM	-23,18	34,52	176,97	142,45	9,12	-1,77	4,77	1,59	-0,70	28,54	0,91	4,09	3,35	2,00	12,38	8,13	4,94	-7,35	1,86	-45,51	
CMM average		-26,22	9,42	95,88	86,46	8,77	0,91	1,37	0,42	3,85	30,83	0,94	2,93	3,88	1,98	11,27	7,80	-0,80	-1,43	2,20	-46,05	
103	Diff.	-15,44	-57,42	64,27	121,69	8,39	-8,19	-1,08	-13,50	-1,00	37,43	1,09		1,08	0,53	11,15	7,59	-5,15	-5,50			
105	Diff.	-14,65	7,45	86,33	78,88	5,13	-10,01	-1,61	-15,14	-0,93	38,17	0,67		4,67	0,85	11,14	6,49	-2,66	-5,99			
129	Diff.	-3,46	-56,30	77,48	133,78	9,12	-9,00	0,57	-11,02	-7,77	28,60	0,92		1,93	0,09	9,40	6,02	-1,57	-8,40			
132	Diff.	-4,65	-57,56	35,55	93,11	4,49	-6,05	-5,82	-9,84	-3,68	25,39	0,55		4,98	0,43	12,26	8,17	0,62	-10,32			
133	Diff.	-5,75	-9,58	167,27	176,85	7,22	-11,67	2,27	-10,91	-9,03	29,54	0,77		2,50	0,50	12,38	7,48	4,99	-14,95			
Difference		**-8,79**	**-34,68**	**86,18**	**120,86**	**6,87**	**-8,99**	**-1,13**	**-12,08**	**-4,48**	**31,83**	**0,80**		**3,03**	**0,48**	**11,27**	**7,15**	**-0,75**	**-9,03**			

Daewoo xy 800 mm/min (Test piece 800mm/min and DBB 400mm/min) – Part design I

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
103	CMM	-32,93	-12,59	74,33	86,92	10,39	1,39	1,82	-1,11	7,31	36,43	1,25	3,46	1,96	2,05	11,14	8,20	-7,67	4,57	11,01	-46,66	-2,85
105	CMM	-32,13	51,28	95,91	44,63	6,99	0,01	0,82	-2,60	7,32	37,17	0,80	2,74	5,51	2,35	11,15	7,14	-1,77	0,67	9,56	-48,47	1,08
129	CMM	-20,90	-11,21	87,61	98,82	11,17	0,43	3,57	1,34	0,61	27,62	1,10	2,78	2,82	1,60	9,38	6,62	-5,03	2,63	7,16	-43,68	-3,95
132	CMM	-22,11	-11,99	45,92	57,91	6,60	3,16	-2,59	2,44	4,68	24,41	0,74	1,56	5,88	1,91	12,25	8,94	-4,55	2,42	11,33	-45,95	-5,91
133	CMM	-23,18	32,80	176,19	143,39	8,88	-0,97	4,04	1,84	-0,81	28,49	0,84	4,09	3,31	1,95	12,38	8,15	10,89	-13,32	9,43	-45,51	6,87
CMM average		-26,25	9,66	95,99	86,33	8,81	0,81	1,53	0,38	3,82	30,83	0,95	2,93	3,90	1,97	11,26	7,81	-1,63	-0,61	9,70	-46,05	-0,95
103	Diff.	-15,50	-56,69	64,63	121,32	8,49	-8,51	-0,68	-13,61	-1,02	37,43	1,11		1,11	0,55	11,14	7,55	-7,62	-3,03			
105	Diff.	-14,70	7,18	86,21	79,03	5,09	-9,89	-1,68	-15,10	-1,01	38,17	0,66		4,66	0,85	11,15	6,49	-1,72	-6,93			
129	Diff.	-3,47	-55,31	77,91	133,22	9,27	-9,47	1,07	-11,16	-7,72	28,62	0,96		1,97	0,10	9,38	5,97	-4,98	-4,97			
132	Diff.	-4,68	-56,09	36,22	92,31	4,70	-6,74	-5,09	-10,06	-3,65	25,41	0,60		5,03	0,41	12,25	8,29	-4,50	-5,18			
133	Diff.	-5,75	-11,30	166,49	177,79	6,98	-10,87	1,54	-10,66	-9,14	29,49	0,70		2,46	0,45	12,38	7,50	10,94	-20,92			
Difference		**-8,82**	**-34,44**	**86,29**	**120,73**	**6,91**	**-9,09**	**-0,97**	**-12,12**	**-4,51**	**31,83**	**0,81**		**3,05**	**0,47**	**11,26**	**7,16**	**-1,58**	**-8,21**			

Daewoo xy 800 mm/min (Test piece 800mm/min and DBB 400mm/min) – Part design II

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-17,43	44,1	9,7	-34,4	1,9	9,9	2,5	12,5	8,33	-1,0	0,14		0,85	1,5	0,0	0,65	-0,05	7,6			
190	CMM	-33,05	94,02	38,62	-55,40	-4,98	17,00	-2,71	17,61	5,92	33,61	-0,46	1,95	0,68	1,85	10,93	3,35	-6,76	4,84	9,00	-47,48	-2,38
191	CMM	-32,11	138,82	79,13	-59,68	-2,51	14,05	-4,58	13,78	5,75	33,93	-0,64	1,71	2,99	1,61	10,04	2,03	-1,03	0,09	8,02	-48,96	1,99
192	CMM	-20,96	75,41	36,86	-38,56	-2,25	16,29	-0,80	14,67	3,84	24,72	-0,39	1,27	0,77	2,44	9,31	3,03	-2,01	1,18	6,49	-44,27	-0,97
193	CMM	-23,28	138,16	148,72	10,56	-4,73	14,44	-1,73	15,66	4,79	26,34	-0,70	2,82	1,87	3,80	10,21	5,87	15,08	-16,42	8,59	-46,02	11,72
194	CMM	-22,17	112,72	24,47	-88,25	-1,23	16,84	-4,66	16,66	8,81	20,95	-0,46	0,21	3,06	2,69	9,15	5,96	-8,36	6,24	10,22	-46,39	-10,99
CMM average		-26,32	111,82	65,56	-46,27	-3,14	15,72	-2,89	15,67	5,82	27,91	-0,53	1,59	1,87	2,48	9,93	4,05	-0,62	-0,81	8,46	-46,62	-0,13
190	Diff.	-15,62	49,92	28,92	-21,00	-6,88	7,10	-5,21	5,11	-2,41	34,61	-0,60		-0,17	0,35	10,93	2,70	-6,71	-2,76			
191	Diff.	-14,68	94,72	69,43	-25,28	-4,41	4,15	-7,08	1,28	-2,58	34,93	-0,78		2,14	0,11	10,04	1,38	-0,98	-7,51			
192	Diff.	-3,53	31,31	27,16	-4,16	-4,15	6,39	-3,30	2,17	-4,49	25,72	-0,53		-0,08	0,94	9,31	2,38	-1,96	-6,42			
193	Diff.	-5,85	94,06	139,02	44,96	-6,63	4,54	-4,23	3,16	-3,54	27,34	-0,84		1,02	2,30	10,21	5,22	15,13	-24,02			
194	Diff.	-4,74	68,62	14,77	-53,85	-3,13	6,94	-7,16	4,16	0,48	21,95	-0,60		2,21	1,19	9,15	5,31	-8,31	-1,36			
Difference		**-8,89**	**67,72**	**55,86**	**-11,87**	**-5,04**	**5,82**	**-5,39**	**3,17**	**-2,51**	**28,91**	**-0,67**		**1,02**	**0,98**	**9,93**	**3,40**	**-0,57**	**-8,41**			

Daewoo xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-17,68	40,6	-11,8	-52,4	1,6	10,5	2,8	13,1	4,33	-2,67	0,00		0,95	1,7	7,65	3,7	-0,2	6,75			
86	Grid	-16,80	-16,27	51,53	67,80	3,75	13,79	4,29	13,08	5,07	1,33	0,08	0,74	0,75	1,98	14,31	10,07	-0,23	5,87	0,20		
Difference		**0,88**	**-56,87**	**63,33**	**120,20**	**2,15**	**3,29**	**1,49**	**-0,02**	**0,74**	**4,00**	**0,08**		**-0,20**	**0,28**	**6,66**	**6,37**	**-0,03**	**-0,88**			

Daewoo xz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	14,75	2,4	19,7	17,3	-0,8	7,1	3,2	6,5	-2,03	-3,67	-0,14		0,65	0,55	0,3	0,15	0,9	0,6			
87	Grid	10,06	-12,99	41,77	54,76	-0,85	6,34	0,82	7,28	1,87	6,29	-0,26	3,55	0,51	2,02	2,08	5,50	-0,61	-2,51	0,41		
	Difference	**-4,69**	**-15,39**	**22,07**	**37,46**	**-0,05**	**-0,76**	**-2,38**	**0,78**	**3,90**	**9,96**	**-0,12**		**-0,14**	**1,47**	**1,78**	**4,35**	**-1,51**	**-3,11**			

Daewoo xz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	13,92	2,6	0,2	-2,4	2,3	7,1	2,1	6,1	-2,0	1,33	-0,02		1,1	0,8	6,75	10,85	0,2	-0,05			
88	Grid	9,37	18,07	47,76	65,83	1,09	7,08	2,18	9,35	5,09	11,33	-0,07	0,63	1,58	1,77	17,76	26,15	-0,06	-1,50	0,41		
	Difference	**-4,55**	**15,47**	**47,57**	**68,23**	**-1,21**	**-0,02**	**0,08**	**3,25**	**7,09**	**10,00**	**-0,05**		**0,48**	**0,97**	**11,01**	**15,30**	**-0,26**	**-1,45**			

Daewoo yz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	5,32	-32,8	-33,8	-1,0	11,3	6,6	14,4	5,7	-2,0	-1,33	-0,19		1,45	0,4	0,55	0,4	-0,3	-0,65			
89	Grid	2,49	-16,98	24,61	41,59	8,98	6,93	11,02	4,73	-2,34	14,06	-0,49	6,02	0,59	1,35	5,47	5,10	0,54	-1,74	0,49		
	Difference	**-2,83**	**15,82**	**58,41**	**42,59**	**-2,32**	**0,33**	**-3,38**	**-0,97**	**-0,34**	**15,39**	**-0,30**		**-0,86**	**0,95**	**4,92**	**4,70**	**0,84**	**-1,09**			

Daewoo yz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	5,26	-34,3	-42,7	-8,4	11,8	6,6	15,6	7,2	-3,0	-4,33	-0,02		1,6	0,75	3,55	11,4	-0,2	-0,35			
90	Grid	2,34	-10,33	65,19	75,53	10,17	8,58	13,94	8,28	-6,14	2,71	-0,10	0,82	1,47	1,43	10,60	26,60	0,33	-1,74	0,53		
	Difference	**-2,92**	**23,97**	**107,89**	**83,93**	**-1,63**	**1,98**	**-1,66**	**1,08**	**-3,14**	**7,04**	**-0,08**		**0,13**	**0,68**	**7,05**	**15,20**	**0,53**	**-1,39**			

Laser-interferometer and electronic level measurements

	x	y	z
Mean reversal positioning error	0,81 µm	0,59 µm	-2,0 µm
Scale error (least squares slope)	-29,9 µm/m	-19,5 µm/m	-19,2 µm/m
Mean reversal roll error	-1,28 µm/m		1,50 µm/m
Mean reversal yaw error	3,44 µm/m	-9,62 µm/m	-0,84 µm/m
Mean reversal pitch error	2,82 µm/m	2,62 µm/m	-1,16 µm/m

Measurements of Makino A55

Makino A55 xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-0,35	5,4	-46,9	-52,3	0,5	2,3	0,0	3,4	2,67	5,0	-0,09		0,85	0,65	0,0	0,0	-0,7	1,15			
62	Grid	-1,94	-1,70	14,69	16,40	0,26	1,99	0,86	2,07	-4,58	-2,63	0,14	1,67	0,29	0,92	0,64	1,19	-0,10	0,28	0,22		G64
63	Grid	-2,42	-2,35	18,22	20,57	0,09	2,07	0,77	2,19	-4,76	-2,20	0,13	1,76	0,32	0,82	0,82	1,02	-0,08	0,29	0,21		G61
Grid average		-2,18	-2,03	16,46	18,49	0,18	2,03	0,82	2,13	-4,67	-2,42	0,14	1,72	0,31	0,87	0,73	1,11	-0,09	0,29	0,21		
62	Diff.	-1,59	-7,10	61,59	68,70	-0,24	-0,31	0,86	-1,33	-7,25	-7,63	0,23		-0,56	0,27	0,64	1,19	0,60	-0,87			
63	Diff.	-2,07	-7,75	65,12	72,87	-0,41	-0,23	0,77	-1,21	-7,43	-7,20	0,22		-0,53	0,17	0,82	1,02	0,62	-0,86			
Difference		**-1,83**	**-7,43**	**63,36**	**70,79**	**-0,32**	**-0,27**	**0,82**	**-1,27**	**-7,34**	**-7,42**	**0,23**		**-0,54**	**0,22**	**0,73**	**1,11**	**0,61**	**-0,86**			

Makino A55 xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-0,35	5,4	-46,9	-52,3	0,5	2,3	0,0	3,4	2,67	5,0	-0,09		0,85	0,65	0,0	0,0	-0,7	1,15			
106	CMM	-3,29	6,56	45,80	39,24	-0,81	-0,06	-0,21	0,69	-6,10	-0,80	0,50	2,41	1,40	0,72	2,85	3,34	-4,12	0,72	3,12	12,65	-10,30
109	CMM	-2,67	18,01	60,01	42,00	-0,74	0,73	0,34	1,41	-7,36	-0,54	0,48	4,12	1,48	0,17	3,43	2,46	-5,18	1,85	3,13	14,33	-11,55
112	CMM	8,15	-34,18	25,90	60,09	-5,04	1,04	-0,21	3,79	1,12	2,54	-0,25	-0,55	1,94	1,98	2,77	4,17	-1,59	1,06	6,10	13,40	-10,05
114	CMM	6,26	-46,81	13,32	60,12	-5,97	2,56	-1,02	5,86	-4,96	1,71	-0,53	-0,33	1,96	0,80	1,43	4,94	2,49	-2,41	5,92	13,83	-5,22
CMM average		2,11	-14,11	36,26	50,36	-3,14	1,07	-0,28	2,94	-4,32	0,73	0,05	1,41	1,69	0,92	2,62	3,73	-2,10	0,31	4,57	13,55	-9,28
106	Diff.	-2,94	1,16	92,70	91,54	-1,31	-2,36	-0,21	-2,71	-8,77	-5,80	0,59		0,55	0,07	2,85	3,34	-3,42	-0,43			
109	Diff.	-2,32	12,61	106,91	94,30	-1,24	-1,57	0,34	-1,99	-10,03	-5,54	0,57		0,63	-0,48	3,43	2,46	-4,48	0,70			
112	Diff.	8,50	-39,58	72,80	112,39	-5,54	-1,26	-0,21	0,39	-1,55	-2,46	-0,16		1,09	1,33	2,77	4,17	-0,89	-0,09			
114	Diff.	6,61	-52,21	60,22	112,42	-6,47	0,26	-1,02	2,46	-7,63	-3,29	-0,44		1,11	0,15	1,43	4,94	3,19	-3,56			
Difference		**2,46**	**-19,51**	**83,16**	**102,66**	**-3,64**	**-1,23**	**-0,28**	**-0,46**	**-6,99**	**-4,27**	**0,14**		**0,84**	**0,27**	**2,62**	**3,73**	**-1,40**	**-0,84**			

Makino A55 xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-0,35	4,8	-56,7	-61,5	0,2	1,9	-0,1	3,3	3,0	3,67	-0,04		0,95	0,3	0,0	0,8	-0,2	0,95			
60	Grid	-1,89	1,78	11,33	9,55	0,13	1,61	0,87	1,67	-3,48	-1,06	0,02	0,35	0,07	0,77	1,43	3,31	-0,02	0,23	0,32	0,00	G64
61	Grid	-2,48	-0,51	15,64	16,14	0,09	1,87	0,91	2,09	-3,11	-0,82	0,02	0,36	0,02	0,76	1,36	3,54	-0,12	0,24	0,28	0,00	G61
Grid average		-2,19	0,64	13,49	12,85	0,11	1,74	0,89	1,88	-3,30	-0,94	0,02	0,36	0,05	0,77	1,40	3,43	-0,07	0,24	0,30	0,00	
60	Diff.	-1,54	-3,02	68,03	71,05	-0,07	-0,29	0,97	-1,63	-6,48	-4,73	0,06		-0,88	0,47	1,43	2,51	0,18	-0,72			
61	Diff.	-2,13	-5,31	72,34	77,64	-0,11	-0,03	1,01	-1,21	-6,11	-4,49	0,06		-0,93	0,46	1,36	2,74	0,08	-0,71			
Difference		**-1,84**	**-4,16**	**70,19**	**74,35**	**-0,09**	**-0,16**	**0,99**	**-1,42**	**-6,30**	**-4,61**	**0,06**		**-0,90**	**0,47**	**1,40**	**2,63**	**0,13**	**-0,71**			

Makino A55 xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-0,35	4,8	-56,7	-61,5	0,2	1,9	-0,1	3,3	3,0	3,67	-0,04		0,95	0,3	0,0	0,8	-0,2	0,95			
107	CMM	4,55	-46,14	29,51	75,65	-2,37	0,28	-1,73	4,71	-21,33	6,24	-0,08	0,19	1,06	0,79	0,00	6,56	1,68	2,70	4,92	18,73	-9,34
125	CMM	7,81	-93,16	13,94	107,10	-6,15	-0,17	-1,55	8,65	0,23	1,62	-0,18	0,15	2,31	0,81	2,28	7,98	-0,40	6,73	7,19	19,09	-13,00
110	CMM	4,43	11,77	57,20	45,43	-5,18	0,73	-3,47	6,88	-17,63	1,66	-0,17	0,19	1,30	0,37	0,20	7,09	0,64	2,38	5,74	18,60	-9,93
127	CMM	1,06	-91,04	45,79	136,83	-3,64	0,30	-1,43	6,07	-1,12	11,88	-0,10	0,31	1,55	0,65	1,41	7,79	-1,35	5,85	4,95	19,82	-12,37
CMM average		4,46	-54,65	36,61	91,25	-4,33	0,28	-2,05	6,58	-9,96	5,35	-0,13	0,21	1,56	0,66	0,97	7,36	0,14	4,42	5,70	19,06	-11,16
107	Diff.	4,90	-50,94	86,21	137,15	-2,57	-1,62	-1,63	1,41	-24,33	2,57	-0,04		0,11	0,49	0,00	5,76	1,88	1,75			
125	Diff.	8,16	-97,96	70,64	168,60	-6,35	-2,07	-1,45	5,35	-2,77	-2,05	-0,14		1,36	0,51	2,28	7,18	-0,20	5,78			
110	Diff.	4,78	6,97	113,90	106,93	-5,38	-1,17	-3,37	3,58	-20,63	-2,01	-0,13		0,35	0,07	0,20	6,29	0,84	1,43			
127	Diff.	1,41	-95,84	102,49	198,33	-3,84	-1,60	-1,33	2,77	-4,12	8,21	-0,06		0,60	0,35	1,41	6,99	-1,15	4,90			
Difference		**4,81**	**-59,45**	**93,31**	**152,75**	**-4,53**	**-1,62**	**-1,95**	**3,28**	**-12,96**	**1,68**	**-0,09**		**0,61**	**0,36**	**0,97**	**6,56**	**0,34**	**3,47**			

Makino A55 xz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-1,75	8,4	-13,8	-22,2	0,5	1,3	0,5	1,4	1,67	3,67	-0,01		1,15	0,55	0,0	0,0	-0,3	0,65			
67	Grid	-3,66	-17,77	15,79	33,56	-0,21	-0,38	0,71	0,35	5,02	-0,79	0,16	1,93	0,33	0,74	0,62	0,85	0,06	0,17	0,41	0,00	G64
68	Grid	-3,55	-15,64	15,93	31,57	-0,33	0,09	0,58	0,24	5,01	-0,94	0,12	1,82	0,64	1,12	0,59	0,74	-0,01	0,17	0,52	0,00	G61
Grid average		-3,61	-16,71	15,86	32,57	-0,27	-0,15	0,65	0,30	5,02	-0,87	0,14	1,88	0,49	0,93	0,61	0,80	0,03	0,17	0,47	0,00	
67	Diff.	-1,91	-26,17	29,59	55,76	-0,71	-1,68	0,21	-1,05	3,35	-4,46	0,17		-0,82	0,19	0,62	0,85	0,36	-0,48			
68	Diff.	-1,80	-24,04	29,73	53,77	-0,83	-1,21	0,08	-1,16	3,34	-4,61	0,13		-0,51	0,57	0,59	0,74	0,29	-0,48			
	Difference	**-1,86**	**-25,11**	**29,66**	**54,77**	**-0,77**	**-1,45**	**0,15**	**-1,10**	**3,35**	**-4,54**	**0,15**		**-0,66**	**0,38**	**0,61**	**0,80**	**0,33**	**-0,48**			

Makino A55 xz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-2,12	9,5	-22,7	-32,2	1,0	1,3	0,4	1,3	2,33	3,33	-0,01		1,3	0,5	0,55	0,85	0,05	0,05			
65	Grid	-3,55	-16,63	17,71	34,34	0,21	-0,32	1,04	0,08	5,75	-1,21	0,04	0,39	0,42	0,60	1,91	2,54	-0,02	0,27	0,64	0,00	G64
66	Grid	-3,61	-17,14	16,90	34,05	0,32	-0,39	0,80	0,09	5,96	-1,26	0,05	0,39	0,42	0,64	2,77	3,34	-0,00	0,22	0,45	0,00	G61
Grid average		-3,58	-16,89	17,31	34,20	0,27	-0,36	0,92	0,09	5,86	-1,24	0,05	0,39	0,42	0,62	2,34	2,94	-0,01	0,25	0,55	0,00	
65	Diff.	-1,43	-26,13	40,41	66,54	-0,79	-1,62	0,64	-1,22	3,42	-4,54	0,05		-0,88	0,10	1,36	1,69	-0,07	0,22			
66	Diff.	-1,49	-26,64	39,60	66,25	-0,68	-1,69	0,40	-1,21	3,63	-4,59	0,06		-0,88	0,14	2,22	2,49	-0,05	0,17			
	Difference	**-1,46**	**-26,39**	**40,01**	**66,40**	**-0,73**	**-1,66**	**0,52**	**-1,21**	**3,53**	**-4,57**	**0,06**		**-0,88**	**0,12**	**1,79**	**2,09**	**-0,06**	**0,20**			

Makino A55 yz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	2,89	0,6	-14,9	-15,5	0,8	0,7	3,3	1,7	-4,0	-19,0	-0,16		1,1	0,45	0,0	0,0	-1,2	0,85			
71	Grid	0,96	1,05	33,18	32,13	2,52	0,18	2,89	0,34	-6,23	6,36	0,08	2,56	0,93	0,49	2,41	0,61	-0,17	-0,53	0,60	0,00	G64
72	Grid	0,83	-0,20	32,52	32,72	2,52	0,22	2,75	0,38	-6,50	6,96	0,07	2,62	0,86	0,48	2,39	0,61	-0,13	-0,54	0,53	0,00	G61
Grid average		0,90	0,43	32,85	32,43	2,52	0,20	2,82	0,36	-6,37	6,66	0,08	2,59	0,90	0,49	2,40	0,61	-0,15	-0,54	0,57	0,00	
71	Diff.	-1,93	0,45	48,08	47,63	1,72	-0,52	-0,41	-1,36	-2,23	25,36	0,24		-0,17	0,04	2,41	0,61	1,03	-1,38			
72	Diff.	-2,06	-0,80	47,42	48,22	1,72	-0,48	-0,55	-1,32	-2,50	25,96	0,23		-0,24	0,03	2,39	0,61	1,07	-1,39			
Difference		**-1,99**	**-0,17**	**47,75**	**47,93**	**1,72**	**-0,50**	**-0,48**	**-1,34**	**-2,37**	**25,66**	**0,24**		**0,20**	**0,04**	**2,40**	**0,61**	**1,05**	**-1,39**			

Makino A55 yz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	1,77	2,8	-24,2	-27,0	0,1	0,8	3,4	1,1	-0,0	-12,3	-0,00		0,45	0,75	1,6	0,9	-0,2	0,1			
69	Grid	2,24	4,56	36,53	31,97	3,38	1,41	1,80	-0,31	-10,32	13,10	0,00	0,41	1,23	0,82	5,72	4,39	-0,10	-0,98	0,62	0,00	G64
70	Grid	0,73	3,47	37,90	34,42	2,33	0,78	2,32	0,75	-7,01	8,70	0,01	0,43	0,93	0,28	5,19	2,95	-0,25	-0,71	0,73	0,00	G61
Grid average		1,49	4,02	37,22	33,20	2,86	1,10	2,06	0,22	-8,67	10,90	0,01	0,42	1,08	0,55	5,46	3,67	-0,18	-0,85	0,68	0,00	
69	Diff.	0,47	1,76	60,73	58,97	3,28	0,61	-1,60	-1,41	-10,32	25,40	0,00		0,78	0,07	4,12	3,49	0,10	-1,08			
70	Diff.	-1,04	0,67	62,10	61,42	2,23	-0,02	-1,08	-0,35	-7,01	21,00	0,01		0,48	-0,47	3,59	2,05	-0,05	-0,81			
Difference		**-0,28**	**1,22**	**61,42**	**60,20**	**2,76**	**0,30**	**-1,34**	**-0,88**	**-8,67**	**23,2**	**0,01**		**0,63**	**-0,20**	**3,86**	**2,77**	**0,02**	**-0,95**			

Laser-interferometer and electronic level measurements

	x	y	z
Mean reversal positioning error	0,56 µm	-0,60 µm	-0,01 µm
Scale error (least squares slope)	2,7 µm/m	-2,6 µm/m	-8,5 µm/m
Mean reversal roll error	5,67 µm/m		
Mean reversal yaw error	-0,15 µm/m	-0,51 µm/m	
Mean reversal pitch error	-1,31 µm/m	0,53 µm/m	

Measurements of Makino A77

Makino A77 xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	1,34	-3,4	14,3	17,7	3,9	1,6	2,0	2,1	1,3	5,0	0,06		0,8	1,1	0,0	0,0	-2,35	1,0			
91	Grid	-3,07	-5,87	45,90	51,76	1,44	0,35	1,76	1,06	2,41	-3,24	0,07	0,72	1,09	0,73	1,27	1,15	-0,44	0,18	0,42		
	Difference	**-4,41**	**-2,47**	**31,60**	**34,06**	**-2,46**	**-1,25**	**-0,24**	**-1,04**	**1,11**	**-8,24**	**0,01**		**0,29**	**-0,37**	**1,27**	**1,15**	**1,91**	**-0,82**			

Makino A77 xy 400 mm/min – Part design I – No upmilling

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	1,34	-3,4	14,3	17,7	3,9	1,6	2,0	2,1	1,3	5,0	0,06		0,8	1,1	0,0	0,0	-2,35	1,0			
126	CMM	5,00	14,09	38,12	24,03	-2,27	1,65	-0,87	3,33	-10,87	8,13	-0,84	0,79	1,15	0,74	3,25	7,83	5,74	-3,99	2,13	30,08	
	Difference	**3,66**	**17,49**	**23,82**	**6,33**	**-6,17**	**0,05**	**-2,87**	**1,23**	**-12,17**	**3,13**	**-0,90**		**0,35**	**-0,36**	**3,25**	**7,83**	**8,09**	**4,99**			

Makino A77 xy 400 mm/min – Part design I

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	1,34	-3,4	14,3	17,7	3,9	1,6	2,0	2,1	1,3	5,0	0,06		0,8	1,1	0,0	0,0	-2,35	1,0			
126	CMM	5,08	15,63	38,90	23,27	-2,05	0,96	-0,18	3,11	-10,70	8,16	-0,73	0,79	1,10	0,77	2,89	7,89	0,41	1,33	5,33	30,08	-6,14
	Difference	3,74	19,03	24,60	5,57	-5,95	-0,64	-2,18	1,01	-12,00	3,16	-0,79		0,30	-0,33	2,89	7,89	2,76	0,33			

Makino A77 xy 400 mm/min – Part design II

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	1,34	-3,4	14,3	17,7	3,9	1,6	2,0	2,1	1,3	5,0	0,06		0,8	1,1	0,0	0,0	-2,35	1,0			
195	CMM	5,08	-29,08	0,47	29,55	5,23	-2,19	6,43	-4,23	-10,39	9,42	0,82	-0,26	0,23	0,49	0,96	7,79	-0,18	2,31	4,65	29,91	-7,18
	Difference	3,74	-25,68	-13,83	11,85	1,33	-3,79	4,43	-6,33	-11,69	4,42	0,76		-0,57	-0,61	0,96	7,79	2,17	1,31			

Makino A77 xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	1,53	-5,8	15,4	21,2	3,7	1,3	1,5	1,6	2,0	-4,0	0,00		0,95	1,05	0,5	0,9	-2,2	1,25			
92	Grid	-2,19	-13,55	49,28	62,83	1,24	0,18	1,56	1,58	-2,98	-1,22	0,01	0,04	1,33	0,81	3,02	2,37	-0,18	0,09	0,82		
	Difference	**-3,72**	**-7,75**	**33,88**	**41,63**	**-2,46**	**-1,12**	**0,06**	**-0,02**	**-4,98**	**2,78**	**0,01**		**0,38**	**-0,24**	**2,52**	**1,47**	**2,02**	**-1,16**			

Makino A77 xz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-1,32	20,4	39,1	18,7	0,9	2,7	3,0	2,5	1,3	2,3	-0,07		2,6	1,05	2,45	0,0	-1,25	-2,7			
93	Grid	-5,92	-6,51	33,65	40,16	0,27	1,21	-0,08	0,61	-13,21	1,39	0,12	0,21	3,27	0,32	4,99	0,98	0,34	1,26	0,47		
	Difference	**-4,60**	**-26,91**	**-5,45**	**21,46**	**-0,63**	**-1,49**	**-3,08**	**-1,89**	**-14,51**	**-0,91**	**0,19**		**0,67**	**-0,73**	**2,54**	**0,98**	**1,59**	**3,96**			

Makino A77 xz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	CyclicH	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	1,82	30,1	48,2	18,1	2,9	2,3	2,4	1,4	-7,3	-1,0	-0,05		1,6	1,45	1,45	2,7	0,15	-1,55			
94	Grid	-8,06	6,59	45,01	38,41	-0,78	0,82	-1,01	2,58	3,03	2,41	-0,02	-0,05	1,54	0,37	6,16	3,58	-1,03	-0,54	1,13		
Difference		**-9,88**	**-23,51**	**-3,19**	**20,31**	**-3,68**	**-1,48**	**-3,41**	**1,18**	**10,33**	**3,41**	**0,03**		**-0,06**	**-1,08**	**4,71**	**0,88**	**-1,18**	**1,01**			

Makino A77 yz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	0,78	25,2	34,4	9,2	1,3	0,5	0,1	2,7	3,3	-11,0	-0,14		2,5	1,35	0,0	0,0	-0,85	-0,7			
95	Grid	-15,39	160,41	197,78	37,37	-1,56	2,61	14,67	5,14	2,22	29,39	-0,39	0,39	4,62	1,62	14,08	1,02	2,17	-1,57	1,36		
Difference		**-16,17**	**135,21**	**163,38**	**28,17**	**-2,86**	**2,11**	**14,57**	**2,44**	**-1,08**	**40,39**	**-0,25**		**2,12**	**0,27**	**14,08**	**1,02**	**3,02**	**-0,87**			

Makino A77 yz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	4,13	13,2	28,2	15,0	2,2	2,0	1,1	3,5	4,7	-24,7	-0,33		2,5	0,85	1,05	2,0	-0,9	-1,7			
96	Grid	14,04	177,90	245,90	68,00	-1,23	8,31	6,72	-0,92	32,20	0,25	-0,06	0,21	3,22	1,73	11,27	7,16	0,61	3,34	2,97		
Difference		**9,91**	**164,70**	**217,7**	**53,00**	**-3,43**	**6,31**	**5,62**	**-4,42**	**27,5**	**24,95**	**0,27**		**0,72**	**0,88**	**10,22**	**5,16**	**1,51**	**5,04**			

Laser-interferometer and electronic level measurements

	x	y	z
Mean reversal positioning error	1,36 µm	0,36 µm	-0,41 µm
Scale error (least squares slope)	1,7 µm/m	11,7 µm/m	-5,3 µm/m
Mean reversal roll error	-0,80 µm/m		-0,10 µm/m
Mean reversal yaw error	-0,46 µm/m	0,07 µm/m	-0,22 µm/m
Mean reversal pitch error	0,86 µm/m	-0,95 µm/m	-0,52 µm/m

Measurements of Mazak FH-480X

Mazak FH-480X xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-6,85	-59,2	-53,7	5,5	-1,6	-1,7	-1,7	-0,9	0,67	2,33	-0,20		0,65	0,4	0,3	0,5	-1,1	1,9			
116	Grid	-1,22	-91,20	-41,09	50,10	-3,32	-0,81	-1,88	-0,82	-3,44	-2,82	-0,37	2,16	0,76	0,71	1,86	0,01	0,01	0,92	0,21		
	Difference	**5,63**	**-32,00**	**12,61**	**44,6**	**-1,72**	**0,89**	**-0,18**	**0,08**	**-4,11**	**-5,15**	**-0,17**		**0,11**	**0,31**	**1,56**	**-0,49**	**1,11**	**-0,98**			

Mazak FH-480X xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-7,05	-63,3	-61,3	2,0	-1,0	-0,8	-2,1	-2,0	6,33	6,67	-0,03		0,55	0,5	1,25	0,45	-0,6	1,65			
117	Grid	-0,18	-83,03	-26,17	56,86	-3,00	-1,13	-3,62	-0,31	-4,82	1,76	-0,08	0,12	0,85	0,52	9,53	3,91	-0,39	0,70	0,67		
	Difference	**6,87**	**-19,73**	**35,13**	**54,86**	**-2,00**	**-0,33**	**-1,52**	**1,69**	**-11,15**	**-4,91**	**-0,05**		**0,30**	**0,02**	**8,28**	**3,46**	**0,21**	**-0,95**			

Mazak FH-480X xz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	BackM V	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	4,39	-9,3	-61,3	-52,0	-2,0	1,8	-1,5	0,5	-3,33	3,67	-0,11		0,65	0,65	0,4	0,0	-3,4	1,6			
119	Grid	3,38	-42,07	-28,17	13,90	-3,53	-0,11	-2,10	0,23	-2,82	3,18	-0,17	1,60	0,36	0,34	1,33	0,86	0,13	0,02	0,24		
	Difference	**-1,01**	**-32,77**	**33,13**	**65,9**	**-1,53**	**-1,91**	**-0,60**	**-0,27**	**0,51**	**-0,49**	**-0,06**		**-0,29**	**-0,31**	**0,93**	**0,86**	**3,53**	**-1,58**			

Mazak FH-480X xz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	5,01	-12,2	-59,3	-47,1	-1,6	2,0	-1,7	0,6	-2,67	5,33	-0,04		0,75	0,6	1,9	4,2	-0,3	0,7			
121	Grid	3,73	-35,43	-21,11	14,32	-3,28	0,48	-3,70	0,63	-3,67	8,40	-0,06	0,11	0,62	0,38	10,20	10,18	-0,18	-0,08	0,70		
	Difference	**-1,28**	**-23,23**	**38,19**	**61,42**	**-1,68**	**-1,52**	**-2,00**	**0,03**	**-1,00**	**3,07**	**-0,02**		**-0,13**	**-0,22**	**8,30**	**5,98**	**0,12**	**-0,78**			

Mazak FH-480X yz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	3,20	39,9	12,4	-27,5	-1,7	0,3	-1,2	1,6	1,67	-3,0	0,02		0,6	0,35	0,4	0,0	-0,6	0,85			
122	Grid	5,27	66,17	66,92	0,75	-3,14	-0,04	-2,50	0,73	3,84	-1,18	-0,20	1,68	0,27	0,15	1,59	0,30	-0,05	-0,28	0,34		
	Difference	**2,07**	**26,27**	**54,52**	**28,25**	**-1,44**	**-0,34**	**-1,30**	**-0,87**	**2,17**	**1,82**	**-0,22**		**-0,33**	**-0,20**	**1,19**	**0,30**	**0,55**	**-1,13**			

Mazak FH-480X yz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	3,26	42,9	5,2	-37,7	-2,1	0,0	-0,9	1,7	3,67	-4,33	0,00		0,45	0,55	0,0	3,1	0,2	0,1			
123	Grid	5,63	67,55	69,68	2,13	-3,07	-0,15	-2,01	0,99	4,04	-0,75	-0,02	0,12	0,59	0,31	2,48	11,07	0,21	-0,22	0,80		
	Difference	**2,37**	**24,65**	**64,48**	**39,83**	**-0,97**	**-0,15**	**-1,11**	**-0,71**	**0,37**	**3,58**	**-0,02**		**0,14**	**-0,24**	**2,48**	**7,97**	**0,01**	**-0,32**			

Laser-interferometer and electronic level measurements

	x	y	z
Mean reversal positioning error	1,15 µm	1,32 µm	1,47 µm
Scale error (least squares slope)	-24,2 µm/m	21,1 µm/m	-17,15 µm/m
Mean reversal roll error	1,40 µm/m		-0,46 µm/m
Mean reversal yaw error	1,65 µm/m	1,70 µm/m	1,06 µm/m
Mean reversal pitch error	-1,76 µm/m	0,73 µm/m	0,31 µm/m

Measurements of Mitsui Seiki HR5

Mitsui Seiki xy 400mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-9,65	35,7	5,5	-30,2	-3,2	0,2	2,0	1,5	14,0	-11,67	0,21		0,85	2,5	0,85	0,75	-3,75	7,75		
146	Grid	-10,94	10,05	76,65	66,60	-7,01	-1,36	-8,52	1,03	4,33	-3,79	-0,28	2,24	1,38	0,27	3,40	2,21	-1,09	6,27	0,67	
Difference		**-1,29**	**-25,65**	**71,15**	**96,80**	**-3,81**	**-1,56**	**-10,52**	**-0,47**	**-9,67**	**7,88**	**-0,49**		**0,53**	**-2,23**	**2,55**	**1,46**	**2,66**	**-1,48**		

Mitsui Seiki xy 400mm/min – Part design I – No upmilling

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-9,65	35,7	5,5	-30,2	-3,2	0,2	2,0	1,5	14,0	-11,67	0,21		0,85	2,5	0,85	0,75	-3,75	7,75		
153	CMM	-7,80	105,31	114,69	9,37	-11,47	-2,21	-13,35	-0,20	-1,67	-1,26	-1,07	3,64	0,84	1,87	5,81	5,90	2,02	0,69	3,07	13,93
158	CMM	-11,72	53,23	33,40	-19,83	-12,14	-5,50	-13,04	1,94	-0,79	-4,12	-0,98	-0,50	1,05	1,01	5,49	7,30	3,49	1,96	3,32	12,23
CMM average		-9,76	79,27	74,05	-5,23	-11,81	-3,86	-13,20	0,87	-1,23	-2,69	-1,03	1,57	0,95	1,44	5,65	6,60	2,76	1,33	3,20	13,08
153	Diff.	1,85	69,61	109,19	39,57	-8,27	-2,41	-15,35	-1,70	-15,67	10,41	-1,28		-0,01	-0,63	4,96	5,15	5,77	-7,06		
158	Diff.	-2,07	17,53	27,90	10,37	-8,94	-5,70	-15,04	0,44	-14,79	7,55	-1,19		0,20	-1,49	4,64	6,55	7,24	-5,79		
Difference		**-0,11**	**43,57**	**68,55**	**24,97**	**-8,61**	**-4,06**	**-15,20**	**-0,63**	**-15,23**	**8,98**	**-1,24**		**0,10**	**-1,06**	**4,80**	**5,85**	**6,51**	**-6,43**		

Mitsui Seiki xy 400mm/min – Part design I

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-9,65	35,7	5,5	-30,2	-3,2	0,2	2,0	1,5	14,0	-11,67	0,21		0,85	2,5	0,85	0,75	-3,75	7,75			
153	CMM	-7,79	106,43	115,20	8,77	-11,31	-2,73	-12,83	-0,37	-1,58	-1,24	-0,99	3,63	0,87	1,84	5,77	6,15	-1,91	4,62	6,68	13,93	-4,53
158	CMM	-11,72	54,50	34,00	-20,50	-11,97	-6,06	-12,48	1,76	-0,70	-4,10	-0,88	-0,51	1,11	0,98	5,49	7,81	-0,79	6,25	6,67	12,22	-4,94
CMM average		-9,76	80,46	74,60	-5,87	-11,64	-4,39	-12,65	0,69	-1,14	-2,67	-0,94	1,56	0,99	1,41	5,63	6,98	-1,35	5,43	6,67	13,08	-4,73
153	Diff.	1,86	70,73	109,70	38,97	-8,11	-2,93	-14,83	-1,87	-15,58	10,43	-1,20		0,02	-0,66	4,92	5,40	1,84	-3,13			
158	Diff.	-2,07	18,80	28,50	9,70	-8,77	-6,26	-14,48	0,26	-14,70	7,57	-1,09		0,26	-1,52	4,64	7,06	2,96	-1,50			
Difference		**-0,11**	**44,76**	**69,10**	**24,33**	**-8,44**	**-4,59**	**-14,65**	**-0,81**	**-15,14**	**9,00**	**-1,15**		**0,14**	**-1,09**	**4,78**	**6,23**	**2,40**	**-2,32**			

Mitsui Seiki xy 400mm/min – Part design II

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Upmilling
	DBB	-9,65	35,7	5,5	-30,2	-3,2	0,2	2,0	1,5	14,0	-11,67	0,21		0,85	2,5	0,85	0,75	-3,75	7,75			
197	CMM	-7,82	115,06	154,91	39,84	3,64	-6,00	-0,78	0,36	0,76	0,28	0,89	5,97	2,70	0,58	4,10	6,05	-12,21	8,37	9,78	14,24	-13,87
203	CMM	-11,76	61,02	76,93	15,91	3,22	-7,77	-0,25	-1,16	2,68	-2,10	1,15	2,13	3,37	1,51	3,93	6,97	-9,16	6,83	10,21	12,58	-10,89
CMM average		-9,79	88,04	115,92	27,88	3,43	-6,88	-0,52	-0,40	1,72	-0,91	1,02	4,05	3,03	1,04	4,02	6,51	-10,68	7,60	10,00	13,41	-12,38
197	Diff.	1,83	79,36	149,41	70,04	6,84	-6,20	-2,78	-1,14	-13,24	11,95	0,68		1,85	-1,92	3,25	5,30	-8,46	0,62			
203	Diff.	-2,11	25,32	71,43	46,11	6,42	-7,97	-2,25	-2,66	-11,32	9,57	0,94		2,52	-0,99	3,08	6,22	-5,41	-0,92			
Difference		**-0,14**	**52,34**	**110,42**	**58,08**	**6,63**	**-7,08**	**-2,52**	**-1,90**	**-12,28**	**10,76**	**0,81**		**2,18**	**-1,46**	**3,17**	**5,76**	**-6,93**	**-0,15**			

Mitsui Seiki xy 2000mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	Servo Lag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-10,29	38,10	-41,0	-79,1	-13,7	-3,3	-7,9	-2,0	16,67	-16,33	-0,36		1,0	2,3	1,1	0,9	-1,95	3,25		
147	Grid	-12,00	-1,44	78,29	79,74	-14,39	-3,84	-14,85	-3,61	12,41	-23,05	-0,40	1,36	1,08	0,91	13,29	6,82	-1,44	2,78	1,12	
Difference		**-1,71**	**-39,54**	**119,29**	**158,84**	**-0,69**	**-0,54**	**-6,95**	**-1,61**	**-4,26**	**-6,72**	**-0,04**		**0,08**	**-1,39**	**12,19**	**5,92**	**0,51**	**-0,47**		

Mitsui Seiki xz 400mm/min

ID	Device	Sqquareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	StraightH	StraightV	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-3,36	135,0	12,69	-122,4	-1,5	-3,1	0,0	0,2	15,0	-18,67	0,86		1,55	6,45	1,2	1,5	-1,55	1,35		
148	Grid	-9,83	94,89	72,01	-22,87	-5,14	-7,04	-2,92	-10,44	1,88	-9,10	0,76	4,26	1,93	4,23	2,79	3,68	2,16	0,94	0,55	
Difference		**-6,47**	**-40,11**	**59,32**	**99,53**	**-3,64**	**-3,94**	**-2,92**	**-10,64**	**-13,12**	**9,57**	**-0,10**		**0,38**	**-2,22**	**1,59**	**12,18**	**3,71**	**2,29**		

Mitsui Seiki xz 2000mm/min

ID	Device	Sqquareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	-3,22	143,2	-39,4	-182,6	-14,3	-9,4	-9,5	-7,5	17,0	-27,67	0,33		1,95	6,0	0,55	0,95	-0,3	-0,1		
149	Grid	-7,69	100,81	87,86	-12,95	-12,77	-10,94	-11,97	-14,78	15,95	-26,77	0,38	1,48	0,90	4,90	11,85	3,24	2,36	1,74	1,45	
Difference		**-4,47**	**-42,39**	**127,26**	**169,65**	**1,53**	**-1,54**	**-2,47**	**-7,28**	**-1,05**	**0,9**	**0,05**		**-1,05**	**-1,10**	**11,30**	**2,29**	**2,66**	**1,84**		

Mitsui Seiki yz 400mm/min

ID	Device	Sqquareness	Scale	Scale H	Scale V	BackP H	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	1,25	74,1	-9,5	-83,6	2,6	-0,5	3,9	-3,4	-8,67	3,33	0,65		2,4	6,45	0,25	2,55	0,05	0,4		
150	Grid	5,54	89,79	64,45	-25,34	-0,24	-7,75	3,09	-10,75	2,15	-2,12	0,92	3,28	3,24	2,07	1,86	4,00	-2,69	-0,61	0,72	
Difference		**4,29**	**15,69**	**73,95**	**58,26**	**-2,84**	**-7,25**	**-0,81**	**-7,35**	**10,82**	**-5,45**	**0,27**		**0,84**	**-4,38**	**1,61**	**1,45**	**-2,74**	**-1,01**		

Mitsui Seiki yz 2000mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation
	DBB	1,51	77,3	-86,2	-163,5	-1,8	-9,3	-1,3	-10,0	-11,3	8,67	0,74		2,2	6,05	1,15	0,35	-1,0	1,55		
151	Grid	3,46	99,21	69,22	-30,00	-3,86	-11,70	-2,06	-14,74	-2,02	2,62	0,75	1,37	3,42	1,78	13,45	3,35	-2,31	-0,72	0,97	
Difference		**1,95**	**21,91**	**155,42**	**133,5**	**-2,06**	**-2,40**	**-0,76**	**-4,74**	**9,28**	**-6,05**	**0,01**		**1,22**	**-4,27**	**12,30**	**3,00**	**-1,31**	**-2,27**		

Laser-interferometer and electronic level measurements

	x	y	z
Mean reversal positioning error	20,02 µm	10,10 µm	9,07 µm
Scale error (least squares slope)	15,5 µm/m	28,8 µm/m	-25,9 µm/m
Mean reversal roll error	-0,51 µm/m		0,19 µm/m
Mean reversal yaw error	0,33 µm/m	4,23 µm/m	-1,62 µm/m
Mean reversal pitch error	0,87 µm/m	2,85 µm/m	0,14 µm/m

Measurements of OKK MCH-450

OKK xy 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-6,11	-69,6	-125,3	-55,7	2,9	7,4	3,1	9,2	9,3	10,0	1,13		0,8	1,55	0,35	2,55	0,7	1,6			
174	Grid	-2,49	-112,7	-12,82	99,84	0,86	1,73	1,34	6,13	13,48	3,30	1,43	2,21	1,15	1,62	4,90	7,75	0,65	1,95	3,37		
Difference		**3,62**	**-43,1**	**112,48**	**155,54**	**-2,04**	**-5,67**	**-1,76**	**-3,07**	**4,18**	**-6,7**	**0,30**		**0,35**	**0,07**	**4,55**	**5,20**	**-0,05**	**0,35**			

OKK xy 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-6,41	-62,0	-178,8	-116,8	-1,0	-3,7	-2,1	4,7	25,3	11,7	1,50		0,9	0,9	0,8	2,25	-0,2	1,15			
175	Grid	-3,59	-121,6	30,32	-151,9	-1,86	-7,94	-0,10	-1,80	22,00	5,94	1,69	1,12	1,68	3,50	11,38	7,55	-1,09	0,50	5,39		
Difference		**2,82**	**-59,6**	**209,12**	**-35,8**	**-0,86**	**-4,24**	**2,0**	**-6,5**	**-3,30**	**-5,76**	**0,19**		**0,78**	**2,60**	**10,58**	**5,30**	**-0,89**	**-0,65**			

OKK xz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-3,67	-28,7	-121,8	-93,1	5,2	15,2	4,0	17,9	-8,3	11,0	1,60		1,1	2,75	0,0	0,0	2,4	1,5			
176	Grid	-0,18	-17,55	7,08	24,62	1,83	9,78	2,68	10,09	5,15	-1,83	2,37	2,33	1,50	4,69	2,31	7,02	-0,44	-0,49	5,87		
Difference		**3,49**	**11,15**	**128,88**	**117,72**	**-3,37**	**-5,42**	**-1,32**	**-7,81**	**13,45**	**-12,83**	**0,77**		**0,40**	**1,94**	**2,31**	**7,02**	**-2,84**	**-1,99**			

OKK xz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-2,43	-3,2	-156,9	-153,7	-1,7	5,4	-0,5	12,7	-15,3	8,0	1,55		0,85	2,4	0,3	0,0	1,95	1,0			
177	Grid	0,53	-28,55	-12,54	16,01	-1,83	5,77	-2,54	0,53	-9,25	6,18	1,63	0,90	0,61	2,18	5,05	2,96	-1,56	-0,23	5,86		
	Difference	**2,96**	**-25,35**	**144,36**	**169,71**	**-0,13**	**0,37**	**-2,04**	**-12,17**	**6,05**	**-1,82**	**0,08**		**-0,24**	**-0,22**	**4,75**	**2,96**	**-3,51**	**-1,23**			

OKK yz 400 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-11,37	57,1	-36,2	-93,3	5,0	16,5	9,2	11,4	14,3	86,3	0,92		2,65	2,5	2,5	0,0	1,05	0,15			
178	Grid	-17,77	354,14	347,48	-6,66	1,39	12,80	5,50	10,39	25,81	43,50	-0,17	1,61	3,45	5,62	6,56	8,30	4,44	1,66	10,36		
	Difference	**-6,40**	**297,04**	**383,68**	**86,64**	**-3,61**	**-3,70**	**-3,70**	**-1,01**	**11,51**	**-42,80**	**-1,09**		**0,80**	**3,12**	**4,06**	**8,30**	**3,39**	**1,51**			

OKK yz 2000 mm/min

ID	Device	Squareness	Scale	Scale H	Scale V	Back PH	Back PV	Back MH	Back MV	Straight H	Straight V	Servo Mismatch	ServoLag	Cyclic H	Cyclic V	Spike H	Spike V	Play H	Play V	Random	Compensation	Comment
	DBB	-13,63	55,3	-95,1	-150,4	-1,8	10,3	4,0	5,5	5,7	-0,7	0,14		2,6	2,65	3,95	0,0	-4,25	-6,55			
179	Grid	-23,49	147,30	212,49	65,19	2,66	7,14	-2,87	6,98	31,39	-1,79	-0,22	1,26	7,28	5,36	9,87	4,07	1,19	-3,51	16,17		
	Difference	**-9,86**	**92,0**	**307,59**	**215,59**	**4,46**	**-3,16**	**-6,87**	**1,48**	**25,69**	**-1,09**	**-0,36**		**4,68**	**2,71**	**5,92**	**4,07**	**5,44**	**3,04**			

Description of inspected machine tools

Daewoo ACE-H50X

Three axis horizontal machining centre

Working envelope:	800 x 650 x 650mm
Spindle power:	18kW
Max. feedrate:	24m/min
Max. spindle speed:	6000r/min
Controller:	Fanuc 16M

Makino A55

Three axis horizontal machining centre

Working envelope:	560 x 560 x 560mm
Spindle power:	22kW
Max. feedrate:	24m/min
Max. spindle speed:	12000r/min
Controller:	Fanuc 16M

Makino A77

Three axis horizontal machining centre

Working envelope:	800 x 750 x 770mm
Spindle power:	30kW
Max. feedrate:	30m/min
Max. spindle speed:	10000r/min
Controller:	Fanuc 16M

Mazak FH-480X

Three axis horizontal machining centre

Working envelope:	560 x 560 x 510mm
Spindle power:	22kW
Max. feedrate:	32m/min
Max. spindle speed:	12000r/min
Controller:	Mazatrol M Plus

OKK MCH-450

Four axis horizontal machining centre

Working envelope:	600 x 450 x 500mm
Spindle power:	- kW
Max. feedrate:	- m/min
Max. spindle speed:	- r/min
Controller:	Fanuc 11M

Mitsui Seiki HR5

Three axis horizontal machining centre

Working envelope:	850 x 700 x 750mm
Spindle power:	15kW
Max. feedrate:	- m/min
Max. spindle speed:	3150 r/min
Controller:	Fanuc 11M

A sample case

The sample case presented here consists two main phases: first the creation of a simulated measurement case and secondly the analysing of this measurement. A simulated case is used here to have exact values for deviation types. Thus we can compare the results of the analysis phase directly to the initial values given below.

I Simulation of the measurement case

Some deviation types are first chosen to be included in the simulation. The test path trace is chosen to be similar to the BAS test piece for numerically controlled milling and drilling machines [BAS]. The test piece described in the BAS guide is altered so that the test is possible to perform without actual cutting by a cross grid encoder or some other free form capable measuring device. Also another circle form is added to the test trace in order to have circular interpolation both in clockwise and counter-clockwise directions.

Table 17. Initial magnitudes of deviations

Deviation type	Magnitude
Backlash x	10 µm
Backlash y	5 µm
Lateral play x	4 µm
Scale error x	25 µm
Scale error y	-5 µm
Servo mismatch	0 µm
Squareness	10 arcsec
Vibration	2 µm

Deviations are used in the stepping engine of the simulator software to create a measurement case, which reminds real measurement cases. The simulation case is saved into the ASCII file as a long list of co-ordinate pairs. The positioning file consists altogether 1681 lines in this case.

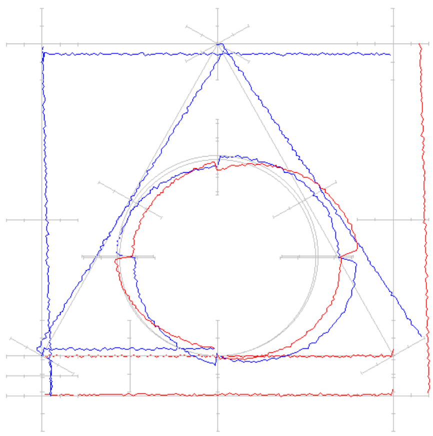


Figure 47. Simulated measurement case

II Analysis

The analysis process goes forward stepwise. Because the computer program makes the actual work and because the process is intricate, not all the details are described here. However all the main tasks are described in such a level that the reader shall be able to replicate the analysis process.

1. Modelling of the theoretical path

A description of the path elements is created. It consists list of features in order of appearance and their attributes. Path description has also identification fields and definition of the measurement plane. This information is required prior reading the positioning file. The path can be stored in the database for the later use.

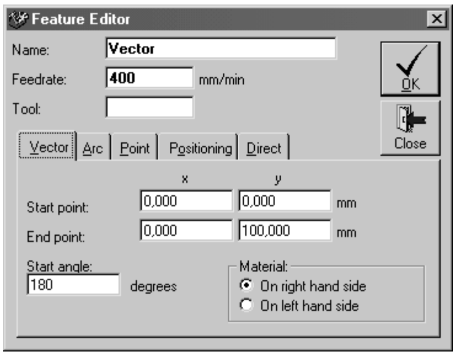


Figure 48. The screen to set-up attributes of a feature

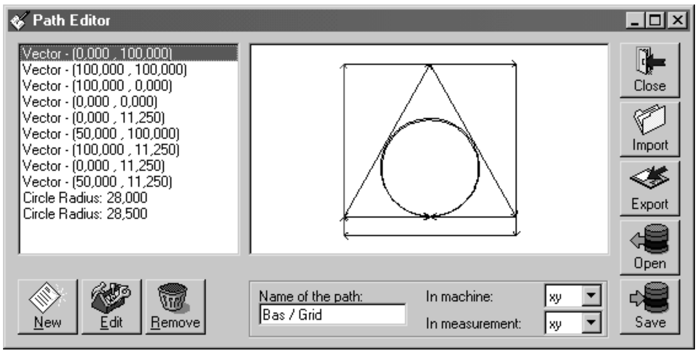


Figure 49. The screen to list all the features in the path description

2. Reading in the positioning file

The positioning file is read in the memory as co-ordinate pairs. If necessary, a co-ordinate conversion or scaling to another measuring units are made.

3. Splitting the measurement to features

We calculate the location of the first co-ordinate pair in relation to the start zone of the first feature [Figure 19]. If the point is located inside the start zone, we consider this point as the start of the feature. If it didn't lie inside the start zone, we proceed to the next co-ordinate pair and check whether that one is inside the start zone.
All the consecutive co-ordinate pairs are now marked to belong to the first feature. Every point is checked whether it lies inside the end zone of the feature. If this happens, the point is marked to be the last point of the current feature and we start to search for the start zone of the following feature.

4. Conversion to local co-ordinate systems

The points belonging to each feature are converted to the corresponding local co-ordinate system. Measurement points are presented with two components the following way:

Table 18. Local co-ordinate systems

Feature type	1st component ($\underline{m}$)	2nd component ($\underline{p}$)
Arc	radial deviation from nominal radius	angular position
Vector	deviation from vector in perpendicular direction	position along vector
Point	deviation in direction of 1st axis	deviation in direction of 2nd axis

5. Search of the suspected cyclic deviation pitch

Sectors from arcs are selected so that they best reflect cyclic deviation behaviour. Search zone of the first axis is around the first axis and the search zone of the second axis around the second axis [Figure 50]. Search zone has to be long enough to occupy at least one full cycle of the longest pitch to search for.
Different possible pitches are stored in a configuration array. Each pitch is fitted to the measurement data using the same method as is presented for the actual deviation fitting. Residual between original measurement data and fitted data is calculated for each pitch. That pitch that has the smallest residual is determined to be the best choice. The same calculation is made individually for both axes.

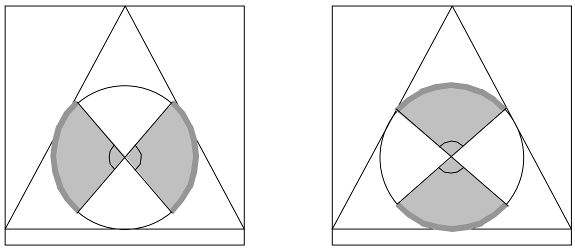


Figure 50. Search zones of the cyclic pitch

6. Creation of prototypes

Deviation prototype vectors are added individually to deviation matrix. Deviation amount is calculated for each value of 2nd component. The required equations are given in the Prototypes chapter [3.5.3]. Always when one vector is ready, the condition of the whole matrix *A* is calculated. If the condition is lower than a preset value, the newly added vector is removed from the matrix. If the condition is high enough, the vector can stay in the matrix. The deviation type vectors are added to the matrix in the following order:

1. Offset of the 1st axis
2. Offset of the 2nd axis
3. Rotation of the test path
4. Tool radius compensation
5. Squareness
6. Scale mismatch of the 1st axis
7. Scale mismatch of the 2nd axis
8. Straightness of the 1st axis
9. Straightness of the 2nd axis
10. Constant backlash of the 1st axis
11. Constant backlash of the 2nd axis
12. Variable backlash of the 1st axis
13. Variable backlash of the 2nd axis
14. Lateral play of the 1st axis
15. Lateral play of the 2nd axis
16. Servo mismatch
17. Cyclic deviation of the 1st axis
18. Cyclic deviation of the 2nd axis
19. Servo lag

7. Calculation of the pseudo-inverse

The pseudo-inverse of the matrix *A* is calculated:

$$A^{\dagger} = (A^{\mathrm{T}} A)^{-1} A^{\mathrm{T}}$$

8. Calculation of the estimates of deviation amounts

We simply multiply out now the estimates for deviations $\underline{d}$ according the following formula:

$$\underline{d} = A^{\dagger}\,\underline{m}$$

9. Calculation of the theoretical path trace

We can calculate back now a theoretical path trace based on the analysis results achieved in the previous phase. This path trace can be used to compare analysis results to original measurement data and it is needed to calculate the estimate of vibration. The theoretical path trace ($\underline{s}$) is retrieved with the following formula:

$$\underline{s} = A\,\underline{d}$$

10. Calculation of the vibration estimate

The standard deviation of the difference between the actual measurement data and the theoretical path trace is calculated. The vibration estimate is now three times the amount of deviation (coverage factor 3). Note, that this vibration estimate does not only involve high frequency vibration but also those low frequency deviations which cannot be explained with the predefined deviation types (see phase 6).

$$d_{vibration} = 3 \times \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[(m_i - s_i) - \overline{(m_i - s_i)}\right]^2}$$

11. Preparing of the results

If necessary, the deviation estimates can be scaled to units that are friendlier to operators. Deviation estimates are also compared to preset control limits to check, if an overshoot or an undershoot has occurred. If a control limit overshoot has occurred, a notification is given to the operator.

12. Presenting of the results

Calculated results are shown to the operator [Figure 51]. The following results [Table 19] are achieved for this particular case. The maximum difference between the analysis results and the initial values of the simulation [Table 17] is this time 2%.

Table 19. Analysis results

Deviation type	Magnitude
Backlash x	10 µm
Backlash y	5 µm
Lateral play x	4 µm
Scale error x	24,7 µm (per the width of the path)
Scale error y	-5,1 µm (per the height of the path)
Servo mismatch	0,1 µm
Squareness	10 arcsec
Vibration	2 µm

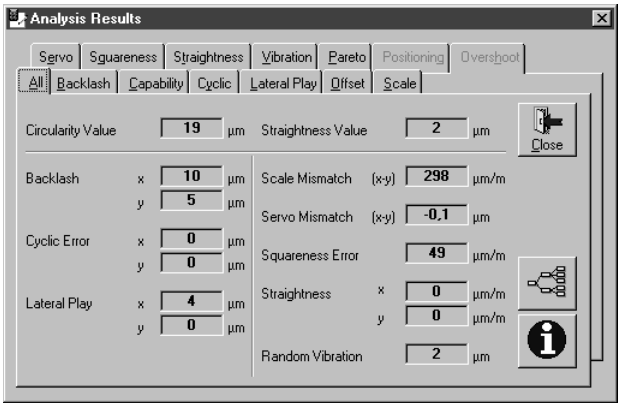


Figure 51. Screen for analysis results

Example printout of the analysis software

Tampere University of Technology
Institute of Production Engineering

Version: 1.2.10

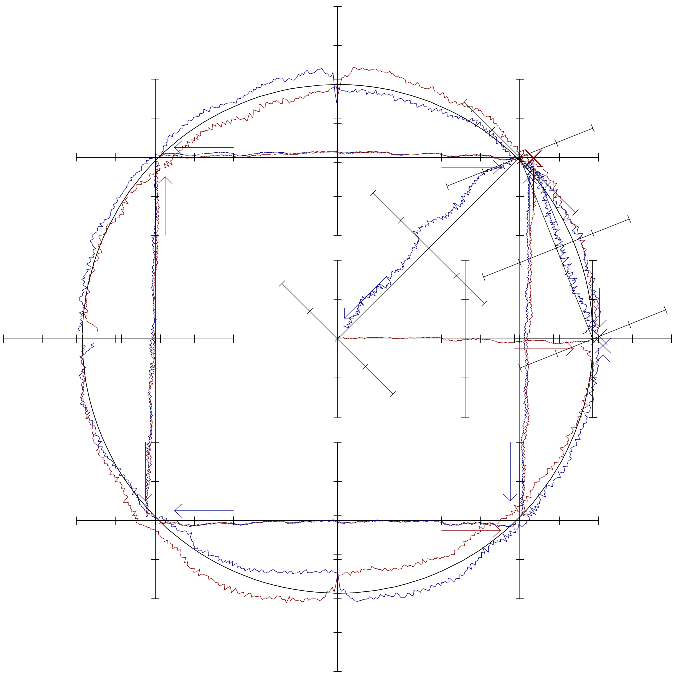
FeatureCheck

Measurement Session:	*Makino A55 / TTEK*	Machine:	*Makino A55*
Date:	*13.10.1997 18:31:41*	Measured By:	*Jouni Hölsä*
Customer:	*TTEK*	Device:	*Grid Encoder*
Piece Name:	*Makino A55 xy 400mm/min*	Origin of Measurement:	*x:0 , y:-480 , z:-377*

Feature	Points	Feedrate	Tool	Feature	Points	Feedrate	Tool
Vector	*286*	*400 mm/min*		*Circle*	*456*	*400 mm/min*	
Circle	*456*	*400 mm/min*		*Point*	*1*	*400 mm/min*	
Circle	*456*	*400 mm/min*		*Circle*	*456*	*400 mm/min*	
Point	*1*	*400 mm/min*		*Vector*	*217*	*400 mm/min*	
Vector	*413*	*400 mm/min*		*Vector*	*413*	*400 mm/min*	
Vector	*413*	*400 mm/min*		*Vector*	*412*	*400 mm/min*	
Point	*1*	*400 mm/min*		*Vector*	*412*	*400 mm/min*	
Vector	*413*	*400 mm/min*		*Vector*	*412*	*400 mm/min*	
Vector	*412*	*400 mm/min*		*Point*	*1*	*400 mm/min*	
Vector	*278*	*400 mm/min*					

Circularity LSC:	*5 µm*	Straightness LS:	*3 µm*
Scale mismatch (x-y):	*-3 µm/m*	Vibration:	*1 µm*
Squareness:	*-12 µm/m*	Servo Mismatch (x-y):	*0,78 µm*
		Servo Lag:	*1,07 µm*

Positional Accuracy x:		Positional Accuracy y:	*1 µm*
Axis Spike x:	*1 µm*	Axis Spike y:	*1 µm*
Backlash x+:	*0 µm*	Backlash y+:	*2 µm*
Backlash x-:	*1 µm*	Backlash y-:	*2 µm*
Cyclic error x:	*0 µm*	Cyclic error y:	*1 µm*
Pitch x:		Pitch y:	
Lateral Play x:	*0 µm*	Lateral Play y:	*0 µm*
Scale error x:	*17 µm/m*	Scale error y:	*20 µm/m*
Straightness x:	*-1 µm / 140mm*	Straightness y:	*0 µm / 140mm*



G61

CW CCW Scale 5,0 µm

Analysis program setup

You can install the analysis program described in this thesis to your computer from the enclosed CD. The program requires PC-compatible computer with Windows 98/NT (or newer) operation system and 8 megabytes free space in the hard disk. Run *setup.exe* in the root folder to start the installation.