

GUIDELINES FOR TRACEABLE MEASUREMENTS ON MACHINE TOOLS

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Abstract:

Flexible manufacturing processes for high quality products at low costs are one of the main research objectives in the field of production technology. The quality inspection of large or complex workpieces manufactured on machine tools often takes place beside the production line. To assure the traceability of the quality inspection the features are measured on a CMM in an isolated measurement room. The high invest for a CMM and influences like transport, handling and the loss of the original set up show the need for a machine tool integrated traceable measuring process for product's quality assurance.

Touch probes can be found in many new machine tools and shall provide the possibility of testing product characteristics right after the manufacturing process. But due to disturbances like machine defects or temperature fluctuations, the measurement process on the machine tool is not traceable. The measurement data are not comparable and cannot be used for process improvements or process control.

New approaches at WZL are aiming to assure the traceability of the inspection processes on machine tools and Multi Technology Platforms (MTP). The fusion of appropriate methods for the traceability of CMM's and innovative calibration methods for machine tools will allow the determination of a measurement uncertainty for the measurement system "touch probe and machine tool". Different methods for the uncertainty evaluation of CMMs have been examined and validated for machine tools. Within the research activities a guideline has been developed that will allow the implementation of a traceable measurement process on machine tools.

The objectives of the research activities are part of the Cluster of Excellence 'Integrative Production Technology for high Wage Countries' at the RWTH Aachen.

Keywords: Traceability, Large Volume Metrology, Machine Tools

1. MOTIVATION

Some of the rapidly growing industries of this millennium can be found in the fields of energy and mobility. Applications in wind energy, aviation and space technology require an increasing number of sophisticated and individualized large components. Due to close tolerances in the large work volumes, the production and testing of these components often encounters the limits of manufacturing and production metrology. But the measurement of large-scale devices is absolute vital for the manufacturing and alignment of many products which modern life depends on.

New concepts and innovative technologies are needed to integrate the measurement processes into the manufacturing process. The monitoring of the processes can enable a "first-time-right" production especially for large and complex components with high value-added production process. This is the main objective of research field of Large Volume Metrology (LVM).

LVM is concerned with the measurement techniques and methods for structures, objects and assemblies with dimensions of a few meters up to tens of meters. These techniques are necessary because the items demand special requirements for the measurement process and the quality control. Structures or objects are usually too large to fit into conventional measuring machines or to be transported to a calibration laboratory. They have to be measured in process or in situ. The trade off between increasing work piece dimensions and constant or even decreasing tolerances (for example in the field of large gears for wind power industries) and the measurement in uncontrolled environments sustainably complicates an accurate and traceable metrology. The regulation pressures in many industries request a metrology, that is able to keep pace with these demands.

1.1 Traceable Measurements on Machine Tools

There are different approaches to achieve traceable LVM processes in the different fields of large volume manufacturing. Integration of the measurement process into large machine tools seems to be one solution to improve the process quality by improving the process knowledge. Consequently this will lead to reduced waste material and a better conformance with the tolerances required in directives or even standards. Especially the possibility of one clamping set up allows re-work processes in the same coordinate system and consequently the improvement of the product quality.

2. TASK

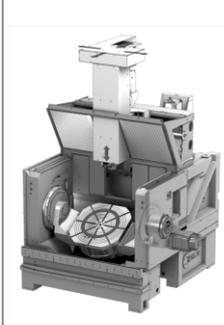
The objective to integrate the measurement process into the machine tool initially seems to be an engineering problem and many machine tools are yet equipped with a touch probe system, that can be automatically loaded. To ensure the comparability of the measurements results to tolerances in technical drawings for example the measuring process has to be traceable. Furthermore the evaluation of the measurement uncertainty is necessary according to DIN 14253-1. The traceability by the uncertainty evaluation for the measuring system is the main scientific objective within this approach. The approach is concerned with the adaption of known methods for the traceability of Coordinate

Measuring Machines (CMM) to the challenges of a machine tool. The traceability can be achieved by the determination of the uncertainty for the measurement process.[1][2][3]

The main challenges must be found in the differences in the kinematic setup of a machine tool and a CMM, the environmental surroundings and the tasks they perform.[4] The geometric errors of the machine tool influence the manufacturing result and seem to prevent the traceable measurement on the machine tool. Consequently the complete knowledge of all geometric errors of the machine tool is the basis for a traceable measurement. The environment of the shop floor means another big challenge to a traceable measurement as the manufacturing or assembly of large-scale devices can hardly take place in expensive controlled environments. Therefore the dominant uncertainty source for the measurement of large scale devices are in time and space varying thermal effects of the environment and the gravitational distortion of both measuring instrument and measured part.[4] The understanding of the behavior of a multiple-part assembly in an uncontrolled environment is still not detailed enough to predict the displacements within the machine tool structure caused by thermal instabilities and gradients. These challenges are addressed in many research projects and programs in the European research community. Issues such as gravitational sag, thermal expansion, thermal diffusivity and thermal effects on instruments and parts have to be tackled by using multidisciplinary approaches involving dimensional and thermal metrology and state-of-the-art modeling.[5]

3. ACTIVITIES

The research for the development of a concept for a traceable machine integrated measurement process is based on a demonstrator located in the laboratories of WZL in Aachen. A machine tool of the type HERMLE C 800 U represents a common five axis kinematic for flexible and precise manufacturing of complex parts. The five-axis machine tool has become increasingly common by the fact, that even complex sculptured surfaces can be machined in a single set-up with versatile tools.[6] Different tactile touch probes can be loaded automatically. The temperature of the surrounding and the machine tool structure is measured by a number of temperature sensors and gradients are monitored.



5 Axis Machine Tool Hermle C 800 U	
Axis	Travel Range
X	0 bis 800 mm
Y	0 bis 600 mm
Z	0 bis 500 mm
A	-90 bis 20 °
C	0 bis 360 °
Kinematic Setup	RRFTTT

Source: Berthold Hermle AG

Fig. 1: Demonstrator Set-Up in the Laboratories of WZL in Aachen, Machine Tool Hermle C800U

The results of the measurement process are validated against a standard. Different standards can be used for a validation such as the Multi-Feature-Check developed by µmetron, Aalen, Germany and ZEISS IMT, Oberkochen, Germany. For the research activities at the WZL a specified standard was designed, manufactured and calibrated. This standard allows the checking of different tolerances such as position, diameter, coaxiality, straightness, angles etc. For the research the diameters of 80 mm (D80) and 40mm (D40) and the straightness for edge A and B (Fig. 2) are chosen. The standard was calibrated at 20°C, therefore the temperature difference between the calibration device and shop floor will mean a gap in the calibration chain. For the research activities a CMM of the type ZEISS Centermax closes this gap. It is located in the same environment as the machine tool and works under the same environmental conditions. So the standard can be calibrated on this shopfloor CMM and used as a reference for the measuring process on the machine tool.

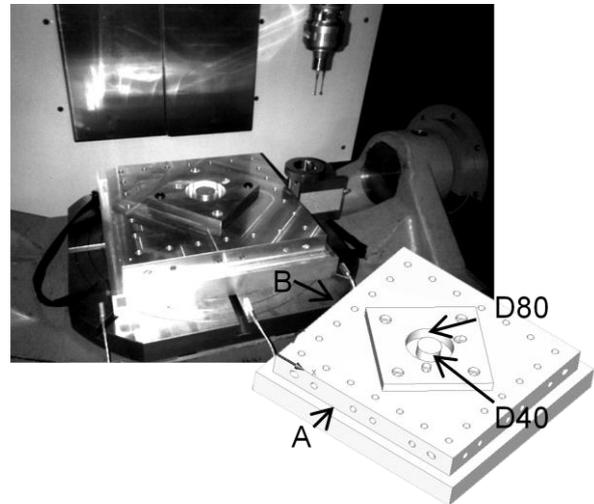


Fig. 2: Certificated Standard measured with Tactile Touchprobe on Machine Tool Hermle C800U at WZL

The research activities concentrate on different methods for a measurement uncertainty evaluation. These methods are used for the establishment of the uncertainty of measurements for a CMM and they are described in ISO 15530 and in VDI 2617. These methods are investigated to be adapted for a determination of the measurement uncertainty for the measurement system consisting of the machine tool and the touch probe.

The general guidance on calculating uncertainty in measurement is given in the ISO Guide 98-3:2008 to the Expression of Uncertainty in Measurement (GUM).[7][8]

The described standard is used for validation by determining the uncertainty as described in DIN ISO 15530 part 3 by using the method of substitution. This experimental approach aims to simplify the uncertainty evaluation by using a calibrated work piece or a referenced standard of a similar geometry and dimension as the measured work piece (similarity standards described in clause 5.2). The measurement strategy for the uncertainty evaluation has to be the same as for the practical measurements. The measurement was carried out fifty times and the uncertainty

was determined by comparing the means of the measured values to the reference values measured on the shop floor CMM.

Another possibility is the establishment of the measurement uncertainty by the use of uncertainty evaluation software (UES). The software uses Monte Carlo methods as mathematical algorithms to compute the results. In joint projects with the Physikalisch Technischen Bundesanstalt in Braunschweig (PTB) the virtual Coordinate Measuring Machine (vCMM) was developed further to be usable for the uncertainty establishment for machine tools as well. The vCMM is an UES that was developed by the PTB and the National Physical Laboratory (NPL) in London.

The third concept is described in VDI 2617-11 and aims to determine the measurement uncertainty by calculating the uncertainty budget for the measurement system and process. The budget consists of listing each uncertainty source, its magnitude, effect on the measurement result and the correlation with the other sources. [7][8]

For a specific measuring task the uncertainty budget consists of the individual contributions to the uncertainty of measurement. The mathematical model is the basis and takes into account that the measuring result is a function of all influencing quantities. The individual contributions can be found in available information such as manufacturer's specifications or calibration certificates. The standard uncertainty (u_c) of the result is the squared sum of all contributions (u):

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + \dots + u_n^2} \quad (1)$$

As the geometric error of the machine tool components and structures is one of the biggest influences for inaccuracy this will also be the main contribution to the measurement uncertainty using the machine tool as a measuring machine.[8] The knowledge of these kinematic errors is the first step in the evaluation of the uncertainty of the measuring system.

The geometric errors of the machine tool can be determined by different direct or indirect measurement methods.[8] Within this project the machine tool was calibrated with a LaserTracer.

4. RESULTS AND GUIDELINES FOR TRACEABLE MEASUREMENTS

In cooperation with the PTB and some industrial partners in the working group *MT-Trace*, the measurement on the machine tool was simulated with the vCMM software. Therefore, the software was adapted to the special challenges of the demonstrator at WZL. Some more research has to be done to validate the adaptations of the software. The inputs for the model are the following information:

- the machine accuracy given as geometric errors of the axis,
- the material, dimensions and certificated geometry of the work piece,
- the uncertainty of the touch probe,
- the temperatures in and around the machine tool structure,
- the measurement strategy.

The results shall be compared to the uncertainty determined with substitution described in DIN ISO 15530-3. The features were measured 50 times. The data were analyzed in Matlab© as needed in the standard. The uncertainty is calculated as described in (1).

$$U = k * \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + b^2} \quad (2)$$

u_{cal} : standard uncertainty calculated from the uncertainty of calibration of the calibrated workpiece (calibration certificate)

u_p : standard uncertainty of the measurement process that is determined with

$$u_p = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (y_i - \bar{y})^2} \quad \text{and}$$

$$\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$$

u_w : standard uncertainty influenced by the material of the work piece

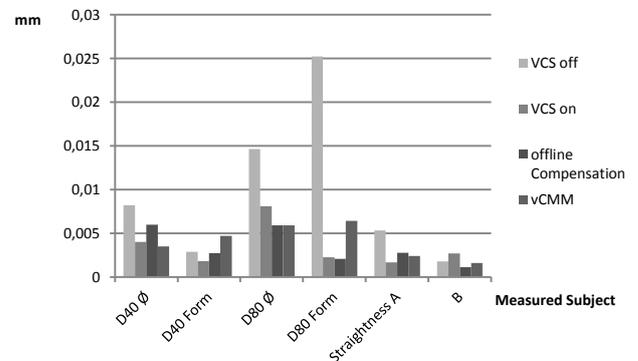
b : systematic deviation between the values y_i indicated by the CMM and the calibration value x_{cal} of the calibrated workpiece ($b = \bar{y} - x_{cal}$)

n : number of measurements

k : coverage factor

The results are shown in table 1. The results named 'VCS off' are uncertainties of measurements on the uncompensated machine tool.

Table 1: Measurement uncertainties on the demonstrator



The systematic errors of the machine tool seem to have an significant impact on the uncertainty of the measurement. A compensation of these errors can reduce the uncertainty. Commercial solutions such as Siemens' Volumetric Compensation System (VCS) or API's Volumetric Error Compensation (VEC) can be used for the compensation. Using VCS on the demonstrator at the WZL the results show the possible improvement in the form of a reduced calculated measurement uncertainty. The knowledge of the kinematic model of the machine tool, the kinematic errors and the uncertainty of the measuring system (LaserTracer) can be used for an offline Compensation of the measured point clouds. The results are shown in the table as "Offline Compensation" and are comparable to the results calculated with the VCS compensated data.

4.1 Guidelines for Traceable Measurements on machine tools

The research activities at the WZL as well as in different industrial cases have examined that there a number of influences that have to be considered implementing a measurement process on the machine tool. The development of a guideline shall help to assure the traceability of this process. The basic measurement system consists of the machine tool, the touch probe system and temperature sensors in the machine tool surroundings and structure. Disturbing factors coming from the environment (temperature, dirt, vibrations etc.) have to be monitored, weighted and minimized. As the main factor seems to be temperature fluctuations in the machine structure temperature changes caused by direct sunlight or open hall doors have to be avoided. As the machine errors are influenced by the temperature of the machine structure the traceability can only be assured for the temperature range during the calibration. The monitoring or surveillance of the measurement system is strongly important for the traceability. Beneath the temperature other influences such as a crash or wear of machine tool and touch probe have to be monitored and the impact on the system has to be considered. The monitoring seems to be one of the key issues. For each measurement the capability of the measurement system for a traceable measurement with the evaluated uncertainty has to be assessed. If the system is not in the specific operation point a traceable measurement is not possible. The user has to wait until the system is capable again or a new evaluation of the uncertainty at this operation point has to be done. There are different methods that have to be investigated for the capability for this assessment.

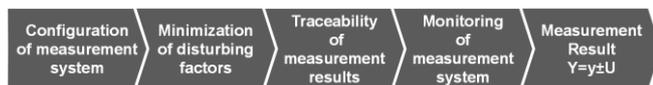


Fig. 3: Steps to a Traceable Measurement on Machine Tool

A number of methods known for calibration and characterization of CMMs or machine tools seem to be capable. The test has to be user-friendly and time effective. The development of an appropriate testing is specific for the used machine tool. Research has to be done.

A new measurement system seems to be appropriate for the testing of numerous machines during production and in the same time. The Absolute MultiLine System is an absolute measuring interferometer based on the Frequency Scanning Interferometry (FSI). It allows an interferometric measurement on up to 24 channels with an accuracy of $0.5\mu\text{m} + 0.5\mu\text{m}/\text{m}$ and a measuring length of up to 20m. The system was developed by the University of Oxford, the NPL and ETALON AG, Braunschweig. The channels can be integrated into the machine tool structure for a permanent testing.

4. OUTLOOK AND FUTURE ACTIVITIES: THERMAL EFFECTS AS SHOW STOPPER

The next steps within the project will address in some more detail the comparison of the different approaches. The

determination of the uncertainty by the uncertainty budget (VDI 2517-11) is in progress. Hereinafter the concept for traceable measurements shall be adapted to the challenges of large machine tools (axes > 5m) and Multi-Technology-Production Systems (MTP). MTP are machine tools with different integrated manufacturing processes. The demonstrator at WZL is part of the Cluster of Excellence 'Integrative Production Technology for high Wage Countries' at the RWTH Aachen University and has been funded by the German Research Foundation DFG. It consists of two working spaces, a common spindle and a robot that handles an innovative laser welding process. Integration of different production processes means the loss of semi-finished products that can be used for a quality control process. Consequently, the quality inspection process has to be integrated into the machine tool as well.

The topic of thermal influences on the machine tool structure has to be intensively investigated, as it is critical for the measurement process as well as for the manufacturing process.[8] The main objective is to predict the static and dynamic behavior of the machine structure under thermal load. Multiple national and international projects have been established this research field, trying to improve the necessary modeling to understand and predict the behavior of large multi-component structures in non-ideal measurement environments. The first step for a complex modeling of a multi-component structure such as a machine tool or a complex work piece is the precise understanding of the effects on the structure. The new Absolute MultiLine System can be integrated into the machine tool structure to map the static and thermal behavior of the machine tool. To focus on thermal influences the machine tool will be placed in a new thermal chamber at the WZL. This chamber allows a controlled change of the thermal surroundings of the machine. In short term, this shall be used for the stability of the thermal surroundings during the measurements. In long term, the collected data shall allow to improve the known rigid body models of machine tools by extending it with dynamic structures.

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