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machining, accuracy,
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ON-MACHINE MEASUREMENT SYSTEMS FOR HIGH-PRECISION WORKPIECES, PRODUCED ON FIVE-AXIS MILLING MACHINES

The paper describes control systems for measuring of complex workpieces machined on numerically controlled machine tools. The area is called “on-machine measurement” (OMM) and means measuring of workpieces still placed in the working space of the NC machine immediately after the NC machining operation. Measuring is performed by a touch probe inserted into the machine spindle and the movements of the probe are programmed to touch the workpiece in pre-selected points of machined surface. This makes it possible to compare the measured points with corresponding points of the CAD model and thus evaluate deviations in the normal direction between the ideal and real surfaces. In the RCMT - Research Center of Manufacturing Technology in Prague, the research of on-machine measurement methods has been performed with the aim to apply this technology for measuring of very precise and complex workpieces, produced on five-axis milling machines. Different types of control systems for three-axis, five-axis and “three and two” axis on-machine measurements have been analysed, verified and tested. The task has been solved as a part of the HARDPRECISION European project with the aim to verify possibilities in replacing application of conventional coordinate measuring machines (CMM) by on-machine measurements methods even for very complex parts with hardly accessible measured surfaces.

1. INTRODUCTION

On-machine measuring is a sort of post-process measuring, which takes place within the working space of the NC machine after finishing the NC machining operation. The machine tool operates here like a coordinate measuring machine (CMM), using the NC machine axes with their measuring systems and servo drives for realization of measuring cycles and operations, similar to measuring operations on a CMM. Not all NC machines can be used to perform highly precise on-machine measurements and not all machining operations can precede this precious and delicate measuring operation. For this purpose, the machine has to dispose with highly sensitive servo-systems in all NC axes and keep highest precision of relative movements between the tool and workpiece within the whole workspace. The workpiece can be measured immediately after preceding machining

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operation only if the operation did not include unacceptable heat dilatations or distortions. For more credible results, the workpiece should be washed and cooled before measuring and the clamping forces should be reduced to minimum. This may introduce some slight changes into the space position of the finished workpiece in the NC machine and thus a coordinate transformation procedure, similar to that used commonly in CMM machines would be a highly desirable function of an NC machine for the application of on-machine measurements.

For automatic measurement of hardly accessible surfaces, automatic NC control of angular A and B axes within the on-machine measuring cycles has shown itself as another important feature of OMM systems. On-machine measurement utilizes experience gained in some well-known measurement procedures, devices and methods. The most important of them are pre- and in-process touch probe measurements and post-process CMM measurements. Some important features of the OMM control systems and measurement features reflecting the state of art of these technologies will be described in the following chapter.

2. THREE-AXIS, FIVE AXIS- AND „THREE PLUS TWO“-AXIS OMM SYSTEMS

2.1. THREE – AXIS MEASUREMENT SYSTEM

During the 2006 period of the HARDPRECISION project, the RCMT worked on the task to finalize and verify a three-axis on-machine measurement system for high-precision workpieces. For most of common workpieces, all measuring points could be approached by the touch probe at one suitable angular position of the workpiece and in case of the five-axis

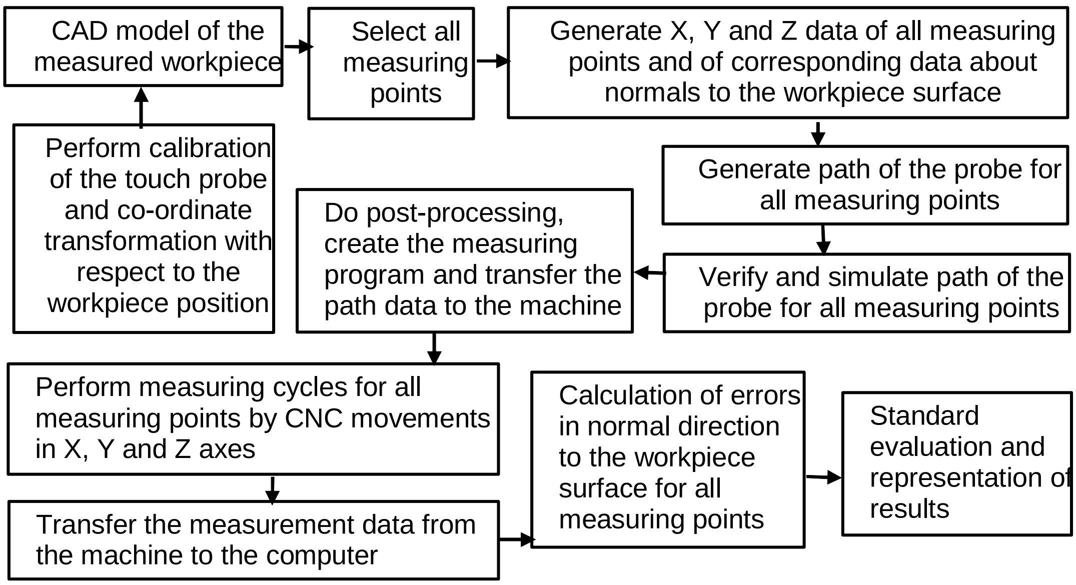


Fig. 1. Basic block diagram of the 3-axis measuring system, finalized in the RCMT laboratory

milling machine, the A and B rotary and tilting axes could be kept stationary during the whole on-machine measurement procedure. In other cases, the workpiece should have suitable reference surfaces which could be approached at two or more independent angular A-B positions of the rotary and tilting table. Than, some sequentially performed partial 3-axis measurements can create satisfactory data for complex evaluation of errors in all selected measuring points.

Within the starting period of the HARDPRECISION project, the RCMT was supposed to finalize and verify simpler 3-axis measurement methods by using their 3-axis CNC milling machines equipped with precise measurement systems and highly sensitive linear motor drives. Types LM-1 and LM-2 3-axis experimental milling machines have been adapted for highest sensitivity of NC movements. Later, the research continued on the five-axis high precision, type "NANO/FOCUS hydrostatic five-axis milling machine of the HEMTECH provenance, installed in the IPT Aachen laboratory. Analysis and comparison of RENISHAW and M&H products has shown much higher accuracy of RENISHAW touch probes and software and a decision has been taken to continue with the research exclusively by application of RENISHAW touch probes and software. Fig. 1 shows the block diagram of the 3-axis measurement system finalized and tested in the RCMT laboratory in cooperation with the RENISHAW Co.

2.2. FIVE – AXIS MEASUREMENT SYSTEM

For complex measuring surfaces, the M&H Co. proposed application of their five axis measuring system with software compensations of touch probe errors. Special feature of this system is the automatic CNC controlled rotation and tilting of the workpiece to angular positions in which the normal to the measured surface in any measured point would be parallel with the Z axis of the machine. This means, that the touch probe, moving in the Z direction, touches the workpiece always with its frontal part and accuracy of measurement will not be influenced by deviations of the probe characteristic at other approach directions. Fig. 2 shows the simplified block diagram of the M&H five-axis measuring system.

Unfortunately the system may bring about some problems. Measuring points on workpieces with concave shapes and grooves may not be accessible by this five-axis measuring method and a combination with 3-axis measurements will be inevitable. Then, the deviations of the probe characteristic at other approach directions may come into effect and may introduce discrepancies between both measuring methods. Certain time problem can arise with calibration of the touch probe, which has to be repeated at any movement in A or B axes. For complex measured surfaces, this calibration would be necessary at every measuring point which would introduce problems with measurement economy, because of a considerable prolongation of the measurement time. This actually means that instead of measuring one single point on the machined surface, we have to measure another five points on the calibration ball. Moreover, the touch probe has to travel from the measured point to the calibration ball, which brings above another loss of time.

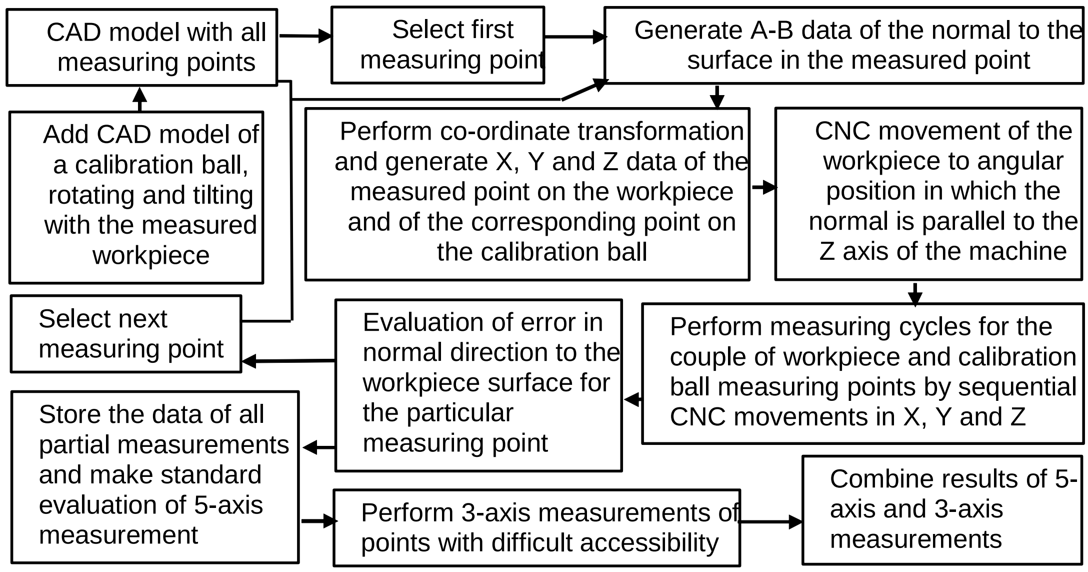


Fig. 2. Simplified block diagram of the M&H 5-axis on-machine measuring system for complex surfaces

2.3. "THREE AND TWO"- AXIS MEASURING SYSTEM

Automatic CNC control of A and B rotary and tilting axes of the NANO-FOCUS five-axis milling machine or other similar machines makes it possible to utilize high "multidirectional" accuracy of RENISHAW touch probes and combine several partial 3-axis

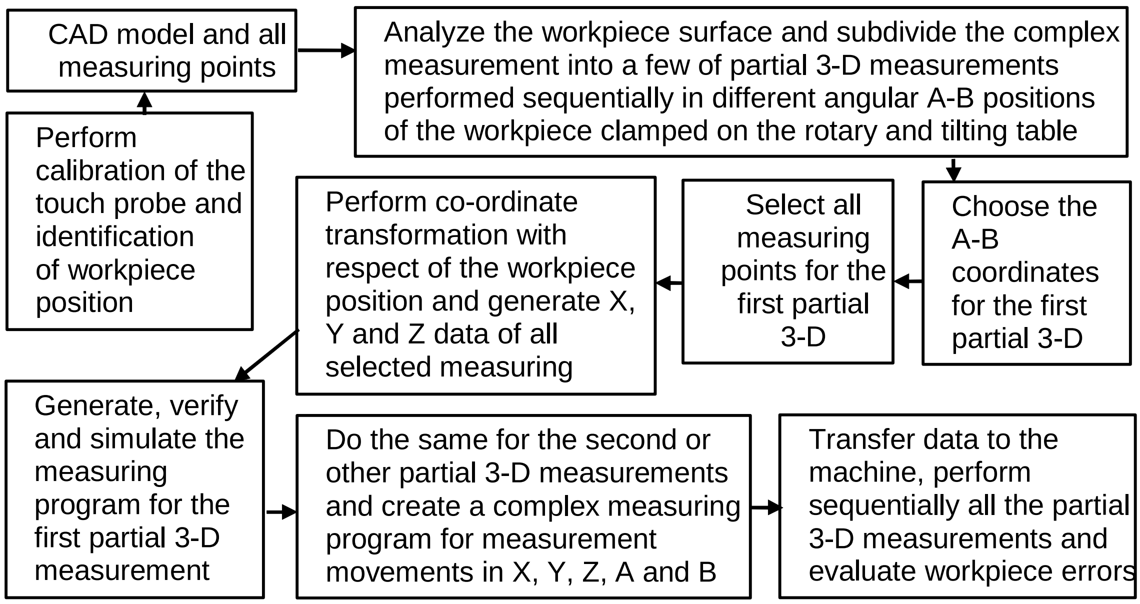


Fig. 3. Simplified block diagram of the RENISHAW 3+2 axis measuring system, verified and tested in RCMT and IPT Aachen laboratories

measurements into one preprogrammed, simulated and verified automatic measuring cycle, which would produce final file of data for standard evaluation and graphic representation of workpiece errors at good accessibility from all space directions. The “best fit” program, which was originally only applicable in partial 3-axis measurements for compensation of machine thermal dilatations, is with the latest version of the RENISHAW “three plus two” system applicable for the final complex file of measured data. Number of movements in A and B axes and number of calibration procedures is reduced to minimum. Each partial 3-axis measurement may involve an additional calibration for compensation of positioning errors in A and B axes and may involve any number of measuring points. Fig. 3 shows its simplified block diagram. This particular system has been evaluated as the best choice for further research and development of on-machine measuring methods and technologies for complex workpieces produced on five-axis milling machines.

3. MULTI-DIRECTIONAL ACCURACY OF TOUCH PROBES

Successful application of “three and two” measuring systems can only be possible in connection with highly precise touch probes. Highest sensitivity, repeatability and “multi-directional” accuracy are crucial parameters of touch probes for such applications. Fig. 4 shows the measurement of multi-directional accuracy of touch probes on the type NANO-FOCUS five-axis milling machine in the IPT Aachen. A high-precision calibrating ball with diameter errors under 50 nano-meters is touched by the touch probe from various space directions. High-sensitivity of machine movements makes it possible to get reliable data about “equatorial” and multi-directional accuracy of applied touch probes.

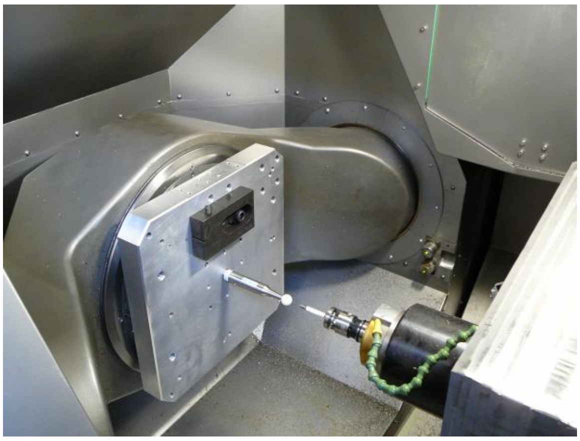


Fig. 4. Measurement of multi-directional errors of probes on the Nano-Focus machine. In the IPTAachen laboratory

Fig. 5 shows “equatorial” diagrams of two types of probes these being the type TX/RX 40.00 M&H mechanical probe with stylus mechanically supported in three points and the type OMP400 tensometric touch probe of RENISHAW provenance. Diagram of the mechanical probe shows expressive “trefoil” effect, causing the radial approach errors in a range of 12μm, whereas the diagram of the tensometric probe has nearly ideal circular shape within the range of 2 μm. More over, repeatability of measuring data is very poor for mechanical touch probes as shown in the Figure 6. This poor repeatability makes the software compensation of probe errors rather problematic. Tensometric probes with their nearly ideal circular characteristics can eliminate superfluous calibrations and in connection with the “three and two”-axis measuring systems considerably reduce the time needed for five-axis OMM cycles.

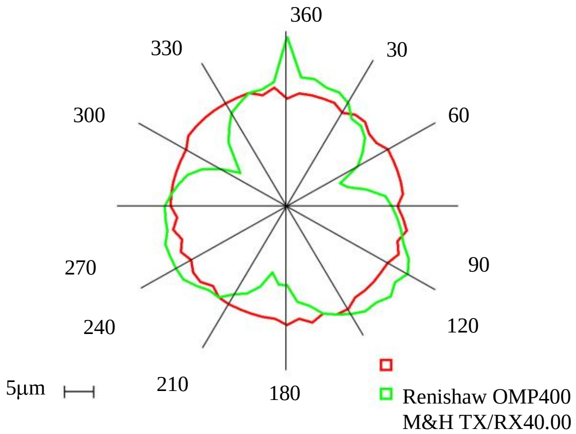


Fig. 5. “Equatorial” diagrams of mechanical and tensometric probes

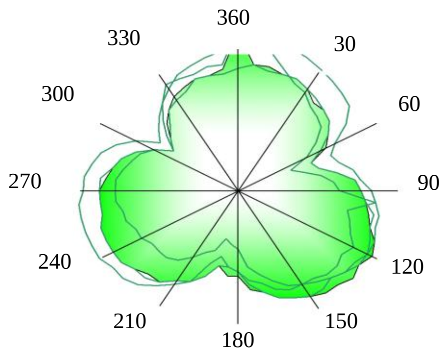
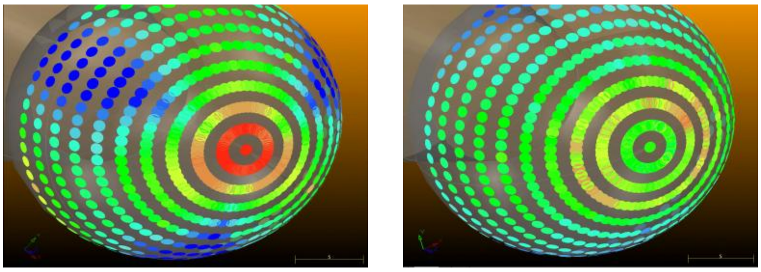


Fig. 6. Equatorial diagram showing poor repeatability of measured mechanical touch probes

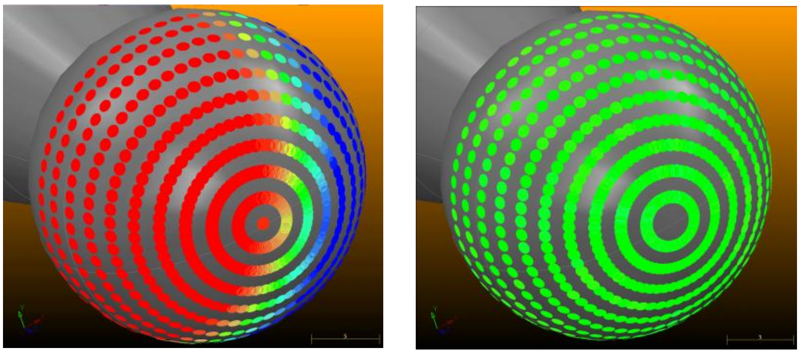


(a) (b)

Fig. 7. Colour-coded spherical representation of touch probe errors measured in 601 space directions: (a) mechanical probe, (b) tensometric probe

Measuring of multi-directional errors of mechanical and tensometric probes has been developed as an automatic OMM procedure in 10 parallel planes on hemispherical surface of calibrating balls in total in 601 approach directions. Results are shown in the Fig. 7 in colour coded representation. For each point, digital error data are available as well. Mechanical probe (a) shows expressive blue strips of the "trefoil" effect and, more over, an additional area of errors at axial approach directions. Similarly like in case of equatorial characteristics, tensometric probes show much better results of multi-directional characteristics.

4. BESTFIT PROCEDURES



(a) (b)

Fig. 8. Effect of the "bestfit" procedure on minimization of displacement errors caused by thermal dilatations: (a) before "bestfit", (b) after "bestfit"

Effect of "bestfit" procedures can be shown on measuring of hemispherical surfaces as well. Fig. 8(a) shows measuring errors at displacement of the ball caused by thermal dilatations or other distorsions of the machine frame, whereas the Fig. 8(b) shows real accuracy of the same surface after "bestfit" compensation. For spherical surfaces, a simpler linear compensation is sufficient. For other surfaces, a full spatial "bestfit" procedure can be applied for compensation of all linear and angular, thermal or weight distorsions of the machine frame. Workpiece deformations from clamping forces cannot be compensated by bestfit procedures and have to be eliminated by technologic means.

5. CONCLUSIONS

1. Within the HARDPRECISION European project, research of on-machine measurement technologies has been performed on three experimental milling machines these being the type LM-1 vertical milling machine and the type LM-2 horizontal milling machine in the RCMT and the type NANO-FOCUS five-axis horizontal milling machine in IPT Aachen

2. All three experimental machines are equipped with linear motors in X, Y and Z axes for highest sensitivity of movements
3. Machines have sufficiently high geometric accuracy and thermal stability and in this respect, they approach the parameters, demanded for application of on-machine measuring methods for highly precise workpieces
4. Three different on-machine measurement systems have been combined with different types of touch probes and analyzed with respect to optimum application for different types of worlpieces
5. Repeatibility and multi-directional accuracy of performed on-machine measurement methods has been checked by measuring of a high precision calibration ball as specimen. Total combined errors of the ball radius, tensometric touch probe and NC measuring scales on the measuring stroke did not exceed the bandwith of a few micrometers.
6. Application of RENISHAW tensometric touch probes and software has shown best repeatability, multidirectional accuracy and effectivity especially for complex workpieces with hardly accessible measured surfaces, machined on five axis milling machines

LITERATURE

[1] ISO 10 791-7., Test conditions for machining centres - Part 7: Accuracy of a finished test piece, 1998.
[2] ZELINSKI P., CAM Software For Probing, http://www.mmsonline.com/articles/110401.html)