Device for Training of Machine Tool Diagnostic Routines under Various Conditions

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Abstract. The article deals with diagnostics of machine tool precision and necessity to train basic routines of measurement and its preparation. Such training is essential for efficiency of diagnostic processes as preparation is usually the most time-consuming and skill-demanding part of overall measurement. The article roughly describes simulation of machine tool errors on proposed experimental device and its implementation into the training process in order to gain experiences with measurement on machine tools in wide scale of conditions. Described device is designed to simulate several geometrical errors, inaccuracies and environmental impacts on precision of positioning which affects not only machine precision but also effectivity of measurement itself.

Introduction

Every manufacturer should desire to effectively produce products of quality required by customer. One of main parameters of product quality is its dimensional and geometrical accuracy which is directly related to the precision of the production machine [1,2]. Machine tool precision is characterized by the ability of the machine to produce parts of the required shape and dimensions keeping the required tolerances and to achieve the desired surface roughness and it is primarily determined by accuracy of the individual parts and its nodes which are produced by conventional methods [3,4]. Dimensions, shapes and relative positions of machine parts are determined on the drawings with tolerances which have to be precisely observed during manufacturing and assembly process. Machine tool inherits certain level of inaccuracies and geometrical errors from its parts, control system and surrounding environment.

Condition of machine tool depends not only on its initial state but also on its usage and maintenance. For further improvement of machine tool reliability and safety during its lifetime the early detection, prediction and localization of inaccuracies and errors is of high interest. Sophisticated techniques of technical diagnostics can be implemented as part of regular maintenance as it provides ability to effectively determine not only actual state of machinery but also future development of important parameters [5,6].

Necessity to avoid machine tool downtimes is sometime in conflict with regular maintenance thesius treatment and often neglected. This can lead to malfunctions of machine tool, producing of scraps or even permanent damage on machine tool [7]. Reduction of time necessary to regular maintenance can achieved not only by omission of diagnostics but also by increasing effectivity of diagnostic processes, what can be done either by using of more effective devices and accessories or by increasing effectively of the diagnostician [8].

It is necessary for such person to be educated and skilled in terms of machine tool diagnostics, its construction and operation in order to perform necessary procedures effectively and correctly. In order to keep such skills and knowledge fresh it is essential to regularly train some routines. Using actual machine tool for training of such routines can be quite difficult because of demand for machine tool in production and keeping of machine tool exclusively for training of measurement.
routines is not financially efficient. Training is important especially for companies dealing mainly with outsourcing of diagnostic processes as service [9, 10].

Training of machine tool diagnostics

Efficiency of performance of machine tool diagnostics is closely linked to difficulty of certain method, its complexity and level of diagnostician’s skills. Example of highly skill-dependent method is measurement of machine tool geometrical characteristics with laser interferometer such as Renishaw XL-80 (Fig. 1). Using such device is considerably difficult therefore it is important to pay close attention to preparation, education and training. Training is important especially for preparation and measurement phases as far as final evaluation of measured data can be done later when machine tool is in normal use again. Preparation phase usually is the most difficult, the most time-consuming and the most skill-demanding part of overall measurement. Operators have to be capable of prediction of whole system behavior. Low level of skills of diagnostician can lead to unwanted prolonging of measurement due problems with initial settings of apparatus what in same cases can lead to unsuccessful measurement and total waste of time spent on diagnostic actions.

Fig. 1. Measuring of precision on EMCO Mill 105 with Renishaw XL-80

It is clear that for implementation of regular training is important to keep skills of diagnostician fresh what can assure efficiency of measurement. Performing proper training requires same key elements as actual diagnostics: measured machine tool, measuring device and performing personnel.

Preparation processes of measurement and initial settings are affected by several aspects such as environment and machine tool state.

Each machine tool is slightly different in terms of geometrical errors even if they are same model, therefore every one of them requires slightly different actions to set measuring device for measurement. It is highly impractical and almost impossible to train on machine with each possible combination of errors because this would require access to huge amount of machines. This would require at least several machines of same construction in extreme conditions.

Luckily, there are at least two another ways to ensure proper training. Nowadays it is very popular to use computer simulations and virtual reality what offers tools to train on machine in virtually any possible condition. Such solution would require significant amount of mathematical interpretations of physical relations between measuring device, machine tool and environment lots of which is not still clear.
Second solution is to build special device representing role of machine tool in measurement process and capable of targeted emulation of faults, inaccuracies and errors. Such device requires just basic functions of machine tool. Control systems of modern machine tools are capable of compensating some dimensional and geometrical inaccuracies. Same principle can be used to emulate such inaccuracies and faults.

**Construction of experimental device for training of diagnostic routines**

We decided to design special device that would be capable substitute of machine tool in training process of positioning precision measurement. Final design of construction (Fig. 2) is very simple. Construction of the device is more similar to three-axis gantry manipulator than to milling machine as there is no need to actual spindle for measurement of positioning. This allowed us to reduce moving masses to necessary minimum and design portable device that can be carried by one man without violating legal limits applicable in the territory of the Slovak Republic and same time keep effective workspace large and stiff enough to perform desired measurements. Fig. 2 does not show worktable in order to keep more important parts visible. Worktable was designed in two variants. First variant uses standardized aluminum profiles with T-slots mounted on frame by screws. Second one uses composite board that consists of plywood with steel sheet glued on top with epoxy. Steel sheet can be used as base for magnetic stands.

![Fig. 2. Model of mechanical structure of experimental device for training of measurement of machine tool precision](image.png)

Designed device construction consists mostly of normalized parts. All non-normalized parts are bended and welded steel sheets. The device could be even lighter if these parts were made of aluminum alloys but measurement devices often use magnets to attach equipment. Guiding of each axis is provided by two inductively hardened guide bars type W with an internal axial thread coupled with AGC type linear sets. Guide bars are also used as carrier elements what significantly reduces weight of construction.

Stepper motors combined with ball screws were used for driving individual axes. Motors and ball screws are fixed together by non-flexible clutch that can reduce some radial and axial forces arising from inaccuracies of motor placement. Each drive is designed to move different mass and reach velocity $100 \text{mm.s}^{-1}$. This design allows us to keep maximal electrical current under 5A at 220V.

Dimensions of all parts were designed and calculated to withstand the maximal loads resulting from the action of drives and weights of construction. Some parts were too complex to be calculated
manually, so models of these parts were tested via stress analysis in Autodesk Inventor Professional 2013 which was also used to design whole construction. With correct material parameters and known maximal forces from stepper motors, screws and inertia of mass we were able to determine maximal deformations of individual parts. Maximal overall deformation was less than 0.3mm, what is enough of stiffness for our purposes.

**Control system**

Easiness of realization, simplicity and reliability are most important features therefor we decided to implement proven ready to use solutions such as Grbl which uses Arduino Mega controller. It is licensed under Gnu GPL license so we can modify source codes as needed. Grbl is commonly used in lots of different kinds of machines such as 3D printers or milling machines. Design of control system is based on Arduino microcontroller, stepper motor drivers and computer connected thru serial port or USB. Physical layer of proposed control system is relatively small and therefor it can be placed in standard plastic switchgear box together with fuses breaker, power source and emergency stop button.

User interface in Grbl (Fig. 3) is very simple and easy to use or even modify, therefor with little programming it can be modified to visually simulate virtually any control system commonly used on standard machine tools. User experience can be further refined by implementation of touchscreen.

![Grbl Controller](image)

**Fig. 3. Standard user interface of Grbl controlling software**

Openness of used control system allow us to modify way it interprets so called G codes to actual movement of end element. This way we can easily emulate wide scale of machine tool faults and inaccuracies. In some cases positioning and movement inaccuracies can be emulated thru direct modification of G-code. Even common CAM software with appropriate postprocessor is capable to prepare such NC program but path of tool have to be precisely planed and programed.

Normally when control system of three-axis milling machine receive command, for example G01 X50 it will move tool along X axis to coordinate X=50. Path of tool should be ideal line but various inaccuracies, wear and other errors can cause that actual path is more or less different than ideal. Deviation between real and programed path can be measured and with correct calibration machine can reduce or in ideal case to eliminate such deviations by using other motors to move against deviation, so on common machine tools this principle is used to decrease influence of errors originating from various inaccuracies of machine tool parts, its damages due collision, wear and so on. Same principle can be used in opposite way to emulate several different faults.
We created computer program with several forms that allow us to setup such deviations simply just by clicking to graph and moving points representing deviations in specific plane. Such form for settings of drive screw wear emulation is shown on Fig. 4. The wear of the drive screw manifests as lag of movement start at change of direction of its movement what can be easily emulated.

![Fig. 4. Form for setting of drive screw wear emulation](image)

For emulation of geometric errors actual path that control system of described device is trying to produce is calculated as function of start, current and end position based on three-dimensional matrix of vectors. Matrix represents workspace itself and vectors stores size and direction of desired deviation. In future we plan to include more variables such as federate, duration of operation and so on in order to widen scale of emulated errors and faults.

**Further improvements and utilization**

Construction of device was designed as stiff enough to perform precisiely enough at maximal feed rate but it still allows us to deform it mechanically by using weights, clamps and uneven surface. This way it is possible to emulate worn, damaged or inappropriately settled machine on which initial settings and measurement itself are even more challenging than normal. Such actions would be very difficult, expansive or even impossible on actual machine tool.

Some environmental impacts also can be part of emulation. For example it is relatively easy to implement vibrations using vibration motors with eccentric rotating mass (ERM) or linear resonant actuators (LRA) mounted on frame of the device. Such motors can deliver various profiles of vibration that can realistically affect behavior of whole system. Frequency and amplitude of generated vibrations can be controlled with simple microcontroller.

Mechanical functions of device can be further extended by adding additional rotary axis in form of simple rotary table that allows even wider range of possible measurements. Described device can be great teaching aid as it can be used with various diagnostic tools as far as they fit into the workspace. Applicability of described device as teaching aid can be improved by extending utility software with teaching module in form of expert system which should containing walkthroughs for measurements and description of measured values.
Technical parameters

The device was primarily designed as a portable substitute of a machine tool that can be used for training of basic routines of measuring positioning precision, especially with a laser interferometer Renishaw XL-80, to perform measurements such as linear measurement, angular measurement, flatness, straightness, squareness, dynamic measurement (velocity and acceleration), measuring of positional stability, feed rate accuracy and stability, interpolation accuracy, and more. It can be used with virtually any system for measuring machine tool precision, for example, with Renishaw Ballbar QC20-W, to measure all axes and even to perform volumetric analysis, which can measure all planes in a single step. The device does not have to be extremely precise as its primary purpose is to simulate a machine tool in not so good condition. Basic technical parameters of the proposed experimental device are as follows:

- Overall weight: 34 kg
- Effective workspace: 400×400×350 mm
- Maximal feed for one axis: 100 mm/s
- Dimensions: 740×650×740 mm
- Power supply: ~230V 5A

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