

Independent Tool Probe with LVDT for Measuring Dimensional Wear of Turning Edge

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Abstract This paper describes an original method for the direct measurement of turning tool wear at the tip of the cutting edge which is performed automatically on an NC lathe with a special probe. The modified probe is equipped with precision displacement sensors. This method of measurement eliminates the errors of touch trigger probes, which are currently used for tool settings and broken tool detection.

In the first original solution, the measurement was conducted using a probe with only one sensor and only in the “-X” direction. The results of laboratory tests show great promise in industrial applications. A new construction of probe allows to measurements to be made in four directions. Apart from the wear measurement, the new probe implements the functionality of standard trigger probe.

1. Introduction

Knowledge about cutting tool condition monitoring is very important. Tool wear significantly influences process costs and machined part quality. The methods of direct assessment of cutting tool edge were developed rapidly in the 1980s. Then, until today, with electronics growing and measurement system prices falling (increasing their speed and availability), indirect methods of cutting tool condition monitoring were developed. There are many industrial systems available now for cutting edge condition monitoring, e.g. methods based on an analysis of component cutting forces, acoustic emission or vibration. These methods are still evolving and much research is carried out in R&D centers.

Many activities in direct cutting edge identification have been practically abandoned (apart from a few exceptions). The Institute of Production Engineering at Warsaw University of Technology has been conducting research on direct tool wear measurement for several years.

2. Concept of direct tool wear measurement

Numerically controlled machine tools are more and more widely equipped with tool probes for fast toolkit tool setup and detection of broken tools/edges. The higher stage of this trend is a new concept of using a special tool probe to measure tool wear [1]. This solution involves the measurement of current wear of the cutting edge (denoted by KE) by checking length changes of tool tip. KE measurement is very important in turning treatment, when the amount

of tool edge reduction affects twice as much the change in diameter of the machined part. For a given tool, KE is proportional to the width of the wear land at the tool point (nose) (denoted by VB_C) with the coefficient dependent on the angles of the edge and it is expressed by equation shown in Fig. 1a. Typically, the KE value is about one tenth of the VB_C value, as shown in Fig. 1b.

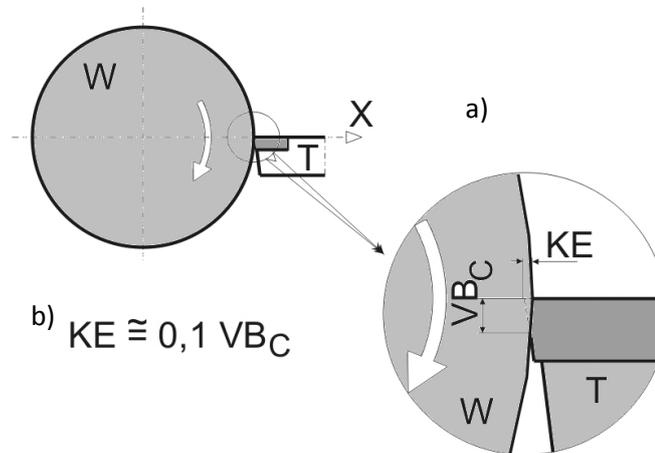


Figure 1. Geometric parameters of tool wear: KE vs. VB_c (a) and typical KE value (b)

If we assume that the maximum value of KE is approximately 0.04 mm, and in most cases it is much less (up to 0.02 mm), it is clear that the measurement should be done with an accuracy of several micrometers.

3. Standard tool probe [2]

Some machine tool producers claim that tool probes with touch trigger sensors, commonly used in NC lathes for automatic determination of the actual position of the cutting edge in an NC coordinate system, can be useful for tool wear evaluation.

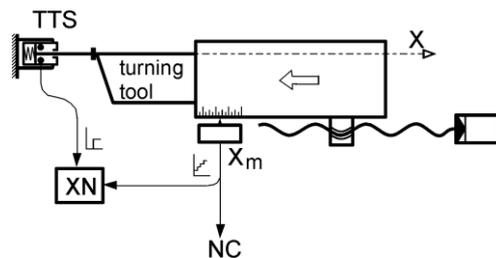


Figure 2. Typical signal track of touch-trigger sensor in NC turning

As shown in Fig. 2, in the case of a standard tool probe, its measurement system is the measuring system of the machine tool. This is important because the accuracy of probe measurement depends on the machine tool state. This practice shows that there are a lot of other influences on the value of XN that are much stronger than KE . First of all, there is the influence of thermal deformations of the lathe and of other elements of the machining system. The procedure is then not so effective at monitoring tool wear. Fig. 3 shows the results of measurements using a standard tool probe with the same unworked tool on the machine tool during normal operation.

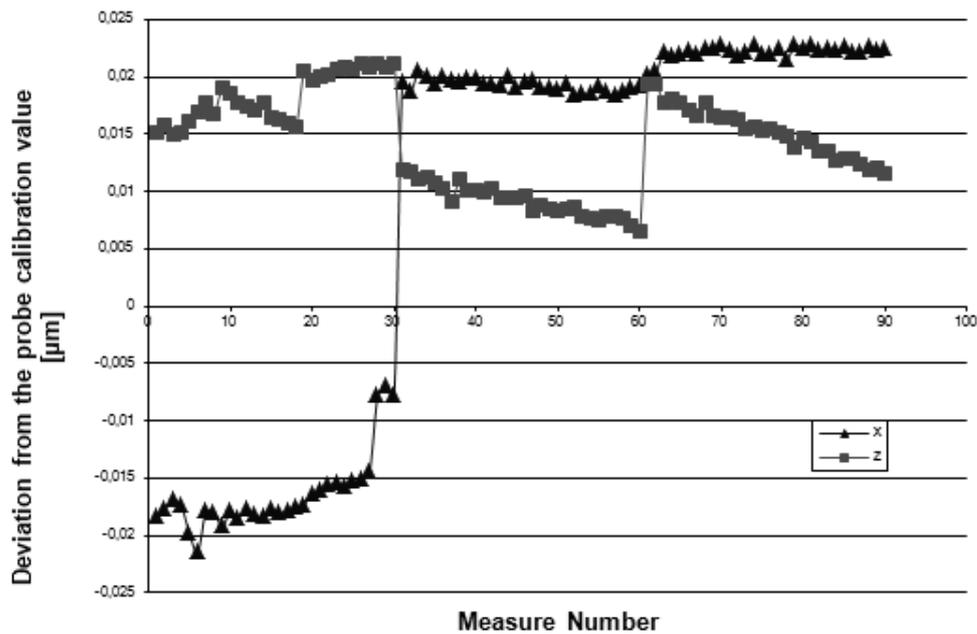


Figure 3. Graphical illustration of measurement - probe RP3 with HPMA arm: measurements from 1 to 30 - immediately after calibration; from 30 to 60 - after 1h heating; from 60 to 90 - after 2h heating

	Number of measurements	Average [mm]	Minimum [mm]	Maximum [mm]	Range [mm]	Standard deviation
X Axis	90	0,0083	-0,0214	0,0228	0,0442	0,0177
Z Axis	90	0,0142	0,0065	0,0211	0,0146	0,0043

Figure 4. Results of statistical calculations - RP3 probe on HPMA arm

As can be inferred from the above charts, the temperature clearly affects the machine coordinate value defined during the procedure of orientating the tool edge tip in the machine coordinate system. The large deviation changes immediately after warming up the machine and then the slow drop in the machine tool Z-axis can be interpreted as the rolling screw of the travelling carriage extension under the influence of temperature and then cooling. This screw is less enclosed than the X-axis screw and it radiates heat faster to the environment.

4. Concept of new tool probe

The concept of the proposed tool wear monitoring system [3,4] was also based on KE measurement by a tool probe, but using a special tool probe. According to this concept, only one displacement sensor (for example LVDT) with a flat tipped finger is used. Another finger with a sharp tip is attached to the body of the sensor. The concept of the probe is presented in Figure 5. The whole sensor may be moved inside the probe, against the force applied by a spring. During measurement, the tool moves toward the probe. The nose of the tool presses against the flat tip of the sensor's finger. When the signal from the sensor reaches a certain value, established in advance (e.g. 1000 µm), the value of the coordinate, derived from the machine tool measuring system, is registered as the position of the tool edge XN. The tool moves farther by an established distance, e.g. 2 mm.

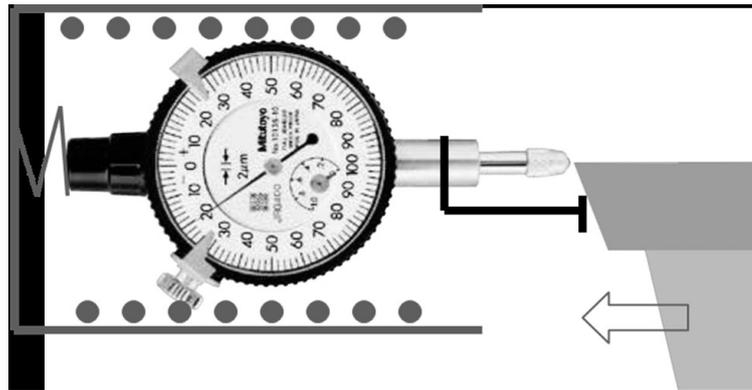


Figure 5. Concept of direct KE measurement

During this movement, the sharp tip of the finger attached to the sensor's body is pressing against a distinctive point of the unworn side surface of the tool used as a reference for the measurement. This makes the whole sensor slide inside the probe against the force of the spring. When the tool stops, the signal from the sensor is registered as $X'N$. The KE value is again calculated as the difference between $X'N_0$ (when the tool was sharp) and $X'N_i$ (measured during monitoring).

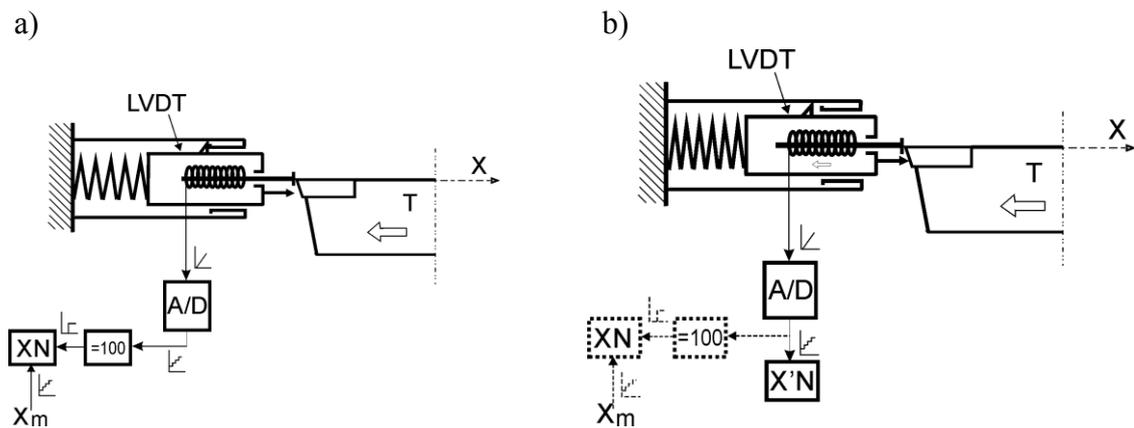


Figure 6. A probe with one LVDT sensor: a) registration of XN , b) registration of $X'N$

The idea behind the new probe is relatively simple. Even more important is the fact that with this kind of design of probe, the distance between the sensor's flat and sharp tips may be small. The reference for the measurement may then be located close to the tool nose, in most cases on the cutting insert itself. In this case, the $X'N$ measurements should be more accurate.

4.1. One direction probe [3,4]

For the new probe, as previously for the standard probe, an analysis of tool wear measurement repeatability was performed. Hundreds of measurements for the same unworked tool at different time intervals and with different thermal states of the machine were made. The results of tool wear in all cases were equal to 0. Similar tests were performed in a workshop environment. The results of tool wear measurements are presented in Fig. 7.

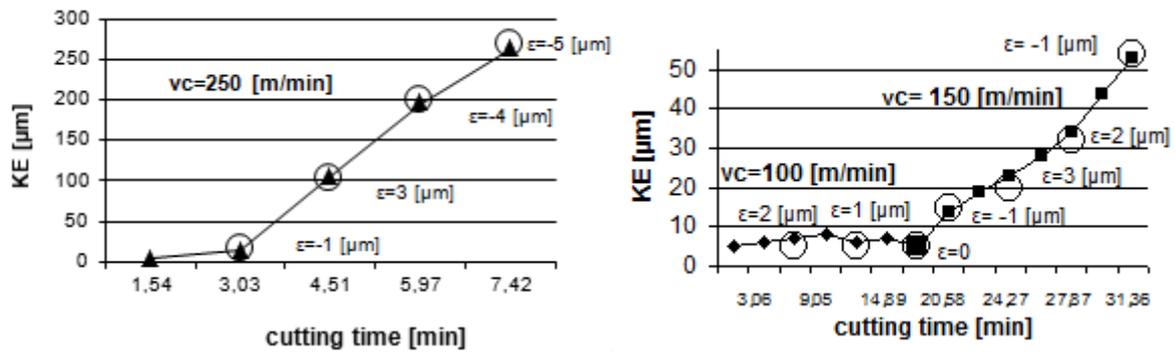


Figure 7. KE values during a test: a) with cutting speed $v_c = 250$ [m/min]; b) when the cutting speed was changed from $v_c = 100$ [m/min] to $v_c = 150$ [m/min] [2]

Two examples of test results are presented. The triangles on the plots represent the results of measurements made with the probe. The circles represent the results obtained during measurements under a tool microscope. When both measurements were made, with the same state of wear, the difference between the measurement by the probe and the KE value measured under the microscope is written on the plot as ϵ .

The test presented in Figure 7b was interrupted after about 32 minutes of cutting because of the very small rate of tool wear. The KE was measured to be only 50 µm.

4.2 Four direction probe

The tool probe described above has a very important limitation: measurements are possible in one direction only. Such a probe does not have the full functionality and universality of a standard tool probe. To be able to replace a standard probe, a new tool probe construction was developed for four direction measurements. Among several concepts, two of the most interesting are described below.

4.2.1 Tool probe with two LVDT sensors

The Linear Variable Differential Transformer (LVDT) is a electromagnetic displacement measuring instrument based the inductive principle during the magnetic core movement inside of three coils (one primary coil and two secondary coils). Due to the cost of the sensors this solution of tool probe proved to be the cheapest one. Necessary size reduction (because of the introduction of a second sensor) was achieved using a miniature displacement sensor without a returning spring MicroEpsilon DTA-1D-0,15 sensors were chosen. They have a body length equal to 40 mm and diameter equal to 10 mm [6].

Tool probe construction was designed so as to minimize the variety of components. Production costs were reduced by measurement system duplication for the two measured axes. The idea behind the structure is shown in the Fig. 8.

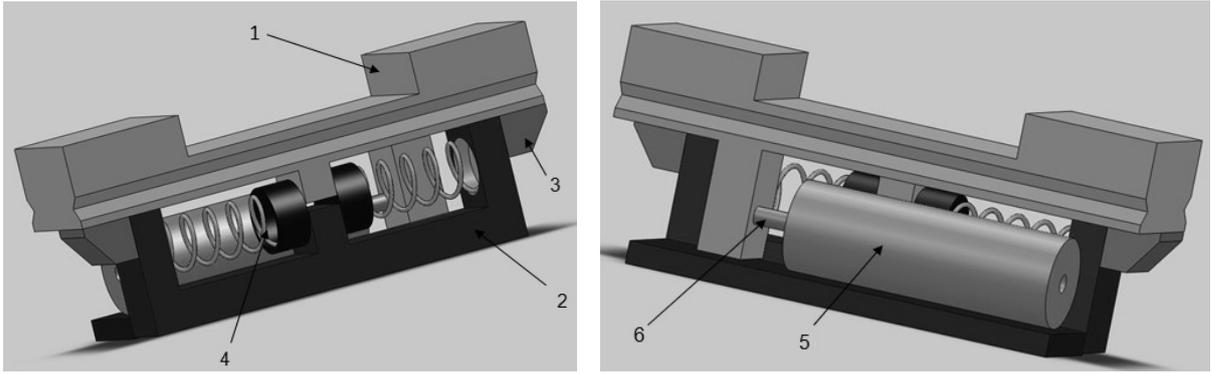


Figure 8. One direction tool probe (bilateral) with displacement sensor

Slider (1) moves in the guides shown in the figure of the body. The body sensor (5) is fixed to the base (2) and to the check tooth (3). The measurement spindle of the sensor (6) is attached to the slider (1). Springs (4) push the slider back to the neutral position.

Fig. 9a shows the movement principle and Fig. 9b shows the complete assembly for four direction measurements.

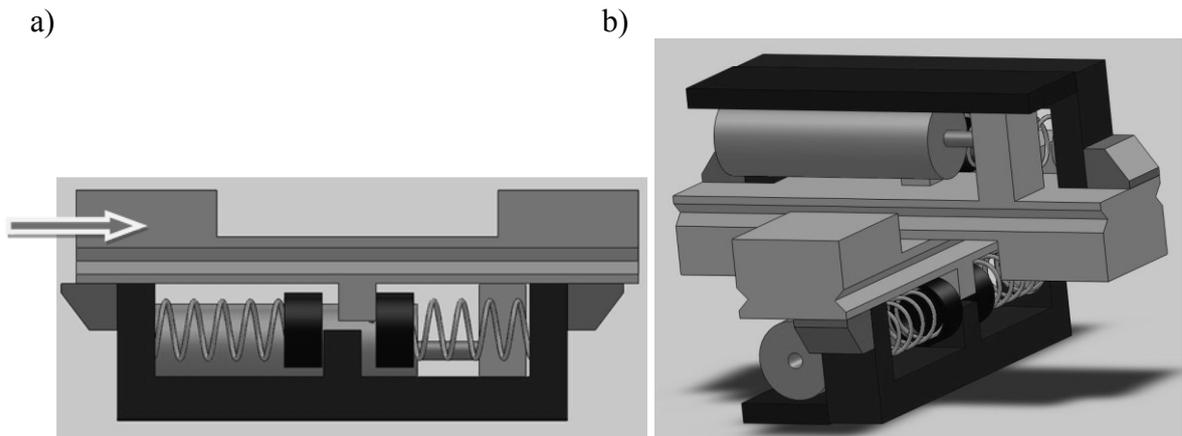


Figure 9. Tool probe during operation (slider pressure force from left) (a) and bidirectional probe (casing not shown) (b)

4.2.2 Probe with capacitive sensors

The second concept of four direction probe was based on capacitive sensors with an additional module which enhances the linearity of the sensor indication. Capacitive sensor parameters are:

- measuring range: 2mm,
- static resolution: 0.02 μ m,
- active area of measurement: $\varnothing = 7.9$ mm,
- improved linearity parameter $\leq + / - 0.1\%$ of measuring range,
- dimensions: L = 24mm, $\varnothing = 20$ mm.

The general concept of the capacitive sensors probe is shown in Fig. 10.

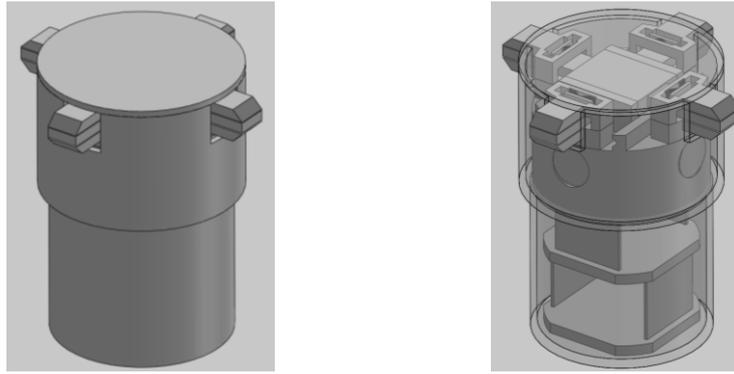


Figure 10. Probe with capacitive sensors

Proposed device structure is totally different like the same principle of sensors measurement (Fig. 11a) financial aspect of the tool probe construction forced sensors quantity limitation up to two sensors. This resulted in a custom measuring system configuration. A standard application of capacitive sensors based on detection of perpendicular target part movement (Fig. 11b).

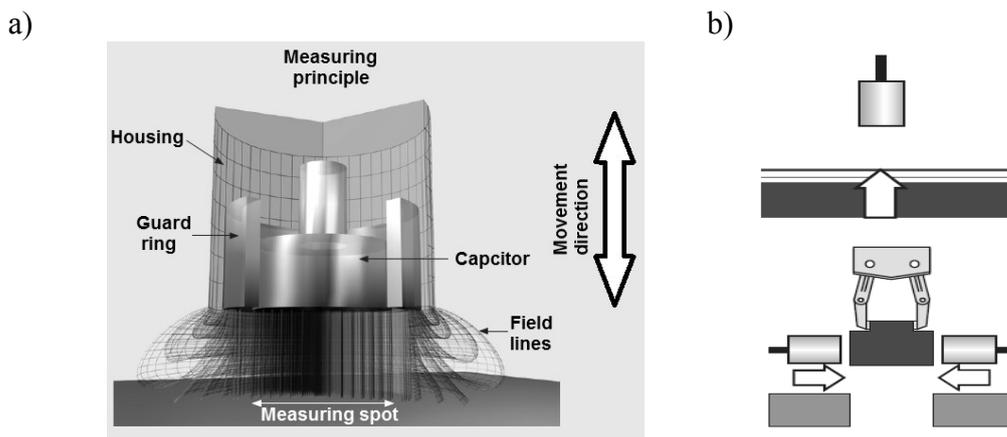


Figure 11. Measurement principle of capacitive sensor (a) and standard application of this kind of sensor (b)

In the variant presented, it was assumed that two sensors would be used to measure four direction movements with only one reference element. Sensor controllers are reliable for synchronization and signal processing (Fig.12).

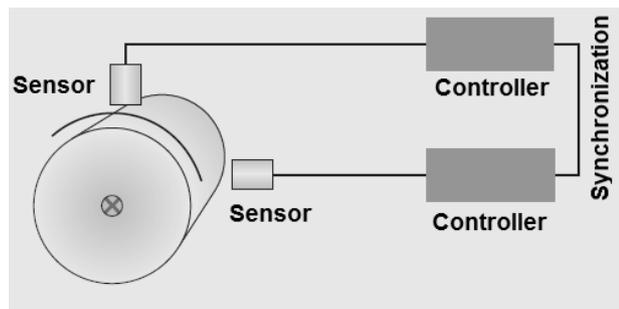


Figure 12. Connection for two capacitive sensors

Planar movements of the reference element (shaft) are registered by two sensors. The flat springs respond as the reference shaft returns to the starting position (Fig. 13).

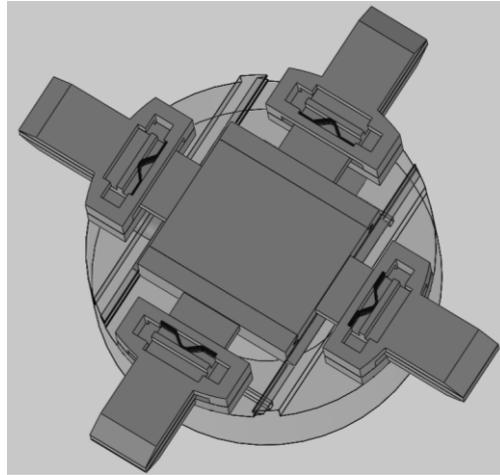


Figure 13. Mechanism with flat springs to force back the movement to the start position

Measurement system duplication shown in case of LVDT tool probe was replaced by a cross-table mechanism (Fig. 14).

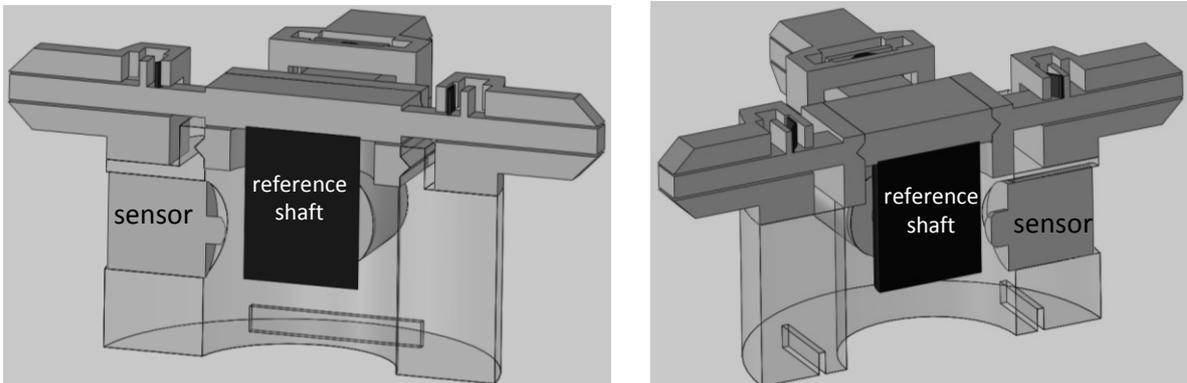


Figure 14. Sectional view of cross table solution with reference shaft and flat springs

Similar design solutions can be used eddy current sensors. It is well known that capacitive sensors are more accurate but they are also more sensitive to pollution from the environment (liquids, etc.). Furthermore, eddy current sensors are sensitive to the heterogeneity of the material (with the exception of aluminum). Irrespective of the sensor type, the measurement path (shown in Fig. 15) is distinguished by a simple structure and the possibility of reconfiguring.

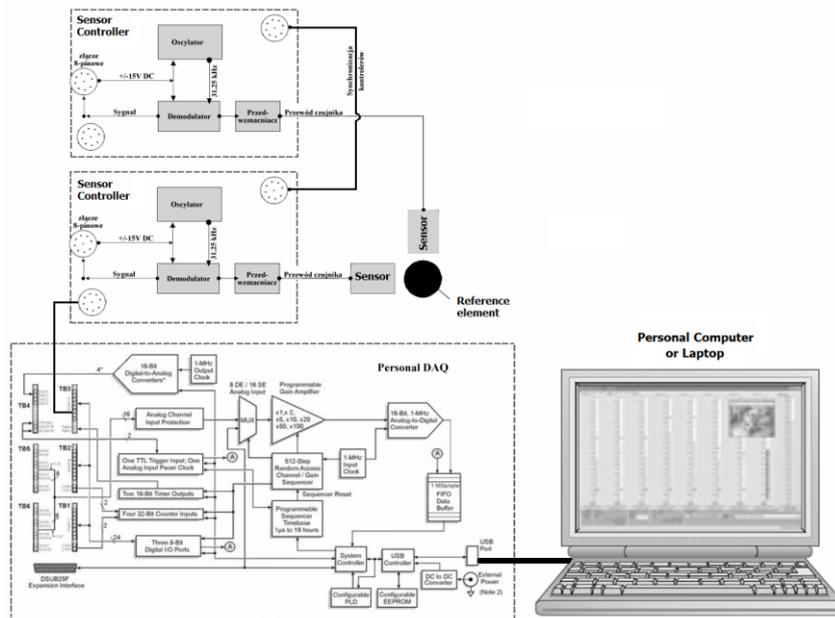


Figure 15. Diagram of measurement path connection to test tool probe

A personal DAQ device (shown in Fig. 16) has a removable screw-terminal input connection to simplify attachment of signals and transducers. It is designed for high accuracy and high resolution data acquisition systems with direct measurement multiple channel ability.

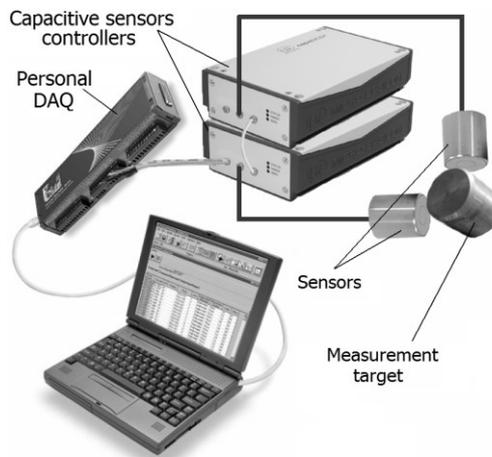


Figure 16. Measurement path components with capability of sensor signal synchronization

5. Conclusions

The results of measurements with a special probe for tool wear detection are encouraging. It was shown that the selection of sensor determines the structure of the probe and is a key aspect of the whole job. Manufacturers and suppliers do not have complete data about the behavior of sensors in such applications. No one was able to give a full answer about the accuracy of measurements in this unusual application of eddy current sensors or inductive

sensors without more complete research, especially when detecting a target that is moving parallel to the sensor instead of changing its distance. The solutions presented are not completely satisfactory. A compromise between price and quality was necessary: precise sensors are very expensive and this excludes them from industrial applications. The optimal solution would be to apply only one non-contact sensor, but this is almost impossible due to the required accuracy.

Acknowledgments

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", No POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

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