XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

TUNING OF AN EXPERIMENTAL DEVICE FOR MEASUREMENT OF DYNAMIC COMPLEX FORCES WHEN TURNING

Petr Chvojka, Jiří Drobílek, Pavel Bach, Miloš Poláček, David Burian, Miroslav Janota

Czech Technical University in Prague, Faculty of Mechanical Engineering, Research Centre of Manufacturing Technology, Prague, Czech Republic, p.bach@rcmt.cvut.cz

Abstract **–** This paper reports on the tuning of dynamic properties of an experimental device used for identification of complex cutting forces that form a new force model, which should ensure a higher accuracy of the stability prediction. The dynamic properties of the device had to be tuned because of the natural frequency present in the working range. An investigation of the appropriate thickness and composition of plate springs and damping interlayers as well as the type of contact grip of the plate springs is the main task of the paper.

Keywords: Self-excited vibration, experimental device, plate spring, natural frequency tuning, damping, complex dynamic forces measurement

1. INTRODUCTION

When machining, technologists are often faced with vibrations existing only at the time of machining. The vibrations are called self-excited oscillations of the tool against the workpiece, in short chatter. The result is a very wavy surface of the workpiece, which is unacceptable both for roughing and finishing. To predict chatter-free cutting conditions in machining, the stability diagram is used, showing the limits of the width of the chip (turning) or the axial depth of cut (milling) depending on the speed of the workpiece or tool. The diagram calculation is based on the measured frequency response function between the tool and the workpiece. The accuracy of the calculation depends on the form of the cutting force model. There are several dynamic forces acting on unstable cutting during turning operations. The forces must be identified experimentally using a test rig described in the paper.

2. EXPERIMENTAL DEVICE FOR TOOL OSCILLATION

In order to verify the new cutting force model, it is necessary to measure dynamic forces under the conditions of an unstable cut, i.e. to create a cutting process during which the tool and the workpiece mutually oscillate during machining at a specific frequency. See Fig. 1. Although this state occurs naturally, the occurrence is neither reliable nor repeatable. Moreover, it is hard to keep this state with constant amplitude for the whole time of measurement.

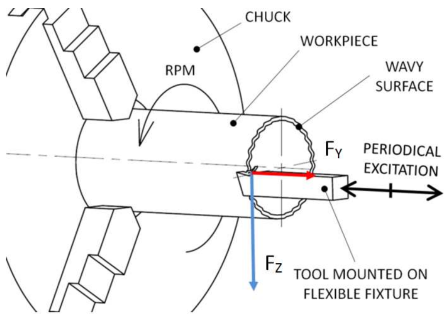

Fig. 1. Schema of the workpiece, tool and total force Fy and Fz

For this reason, an experimental device was designed that would create an unstable cutting process. The device comprises a backlash-free kinematic chain (parallelogram) consisting of flexible plate springs allowing oscillation of the tool during the cut at the required frequency and amplitude (see the scheme of the device in Fig. 2). An electrodynamic shaker is used as a source of dynamic force and required displacement. The force arising in the dynamic cut is measured using three three-axis dynamometers and the current displacement of the tool is measured using an accelerometer or an optical distance sensor.

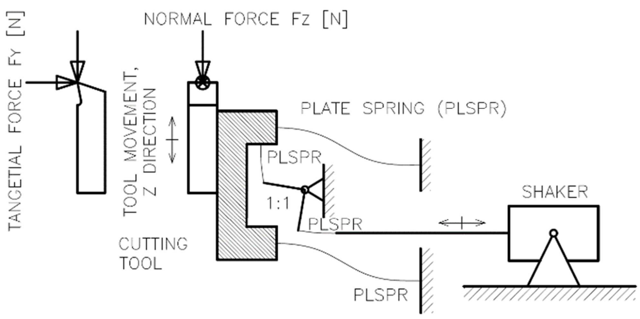

Fig. 2 Kinematic schema of experimental device

The phase shift between the tool oscillation and the waves on the workpiece surface is changed during the tests in the range from 0 to 360 °. The phase shift is changed by a modification to the frequency of tool oscillation. The change in phase shift leads to a change in the orientation of the arising cutting forces.

The resultant of the forces in the direction of the normal and the tangent to the machined surface is calculated as a sum of readings from individual dynamometers in specific directions. Next, a relative phase shift at the frequency identical with the set-up tool oscillation frequency is determined from the spectra of the measured force signal and excited displacement of the tool.

3. ADJUSTING DYNAMIC PROPERTIES OF THE DEVICE – PLATE SPRING TEST RIG

3.1. Purpose of the test rig

Unfortunately, the designed device did not yield satisfactory dynamic properties during initial tests. The natural frequency of the experimental device was in its working range and the results were affected with parasite vibrations. Therefore, it was necessary to experimentally adjust stiffness and damping of the plate springs by selecting their composition and using various damping layers so that their natural frequencies and damping of the experimental device increased. Due to the nonlinearities in the contact layers we preferred the experimental tests instead of analytical (computational) way. For that purpose, a simple plate spring test rig was used in which it was possible to measure these properties simply. See Fig. 3.

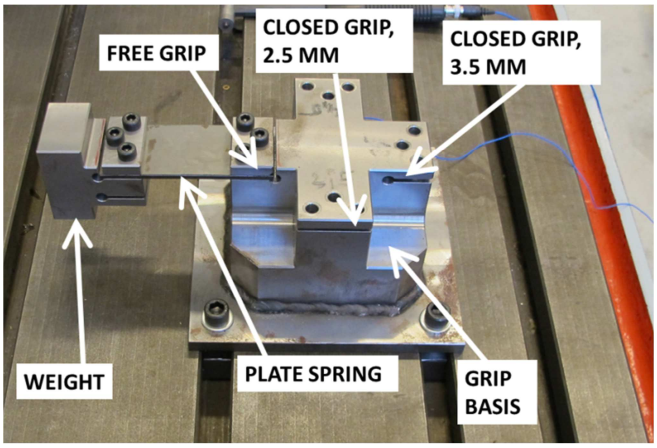

Fig. 3. Plate spring test rig

3.2. Arrangement of tests

As was the case with the experimental device for tool oscillation, the basic frame of the test rig contains two types of plate spring grips (free grip and closed grip). See Fig. 3. and Fig. 4. With the closed grip, the thickness of the groove is made for a specific width of the plate spring (3.5 mm, 4.0 mm and 4.5 mm). Plate springs of any thickness can be clamped into the free grip. The end weight has always the same type of grooves as the basic frame of the test rig. During the test procedure many combinations of plates and dampers were used. The influence of the grip type was investigated as well.

The measurement was performed in the following manner: the measured plate spring (or composition of plate springs and dampers) was clamped into prepared grooves and using a modal hammer and accelerometer its frequency transfer function (FRF) was measured. Excitation technique can be seen in Fig. 4. The modal hammer was hit from above into the weight and structural response was measured by an accelerometer mounted on the lower side of the weight using beeswax.

The instrumentation used for tests is listed below:

- modal hammer PCB 086C04 sens. 1.15 mV/N
- accelerometer 352A21, sens. 9.46mV/g
- NI cDAQ 9178; NI 9234

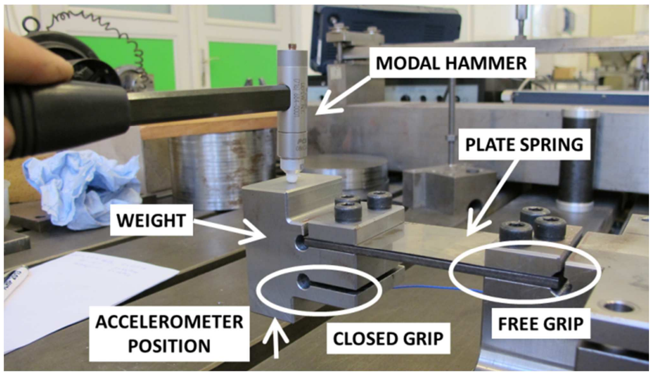

Fig. 4. Measurement of dynamic properties of the plate spring

Variants of plate springs from one piece of sheet metal from various materials were compared with identically thick sandwich structures. The sandwich structures consisted of plate springs of smaller thickness and interlayers from damping materials. PVC foil and paper were used as damping materials. A sandwich from steel sheet metal and polyurethane adhesive as well as a layer of grease between two steel sheets was also used in variants tested. These interlayer materials and their labelling used for sandwich composition can be seen in Fig. 5. The type and thickness of the composed material used in final tested sandwiches are described in the legend placed under each of the FRF graphs. Single plate springs or sandwiches have always the same dimensions: 120mm by 50mm.

Fig. 5. Interlayer materials used in sandwiches

The sandwich was formed by simply stacking these components and clamping them in grips. Fig. 6 shows some of the tested sandwiches; from above: 3x sheet of 1.0 mm with a PVC interlayer, 3x sheet of 1.0 mm with a paper interlayer of square shape (V7 – see Fig. 5.) and 3x sheet of

1.0mm with a grease layer. All of them bolted in the free grips.

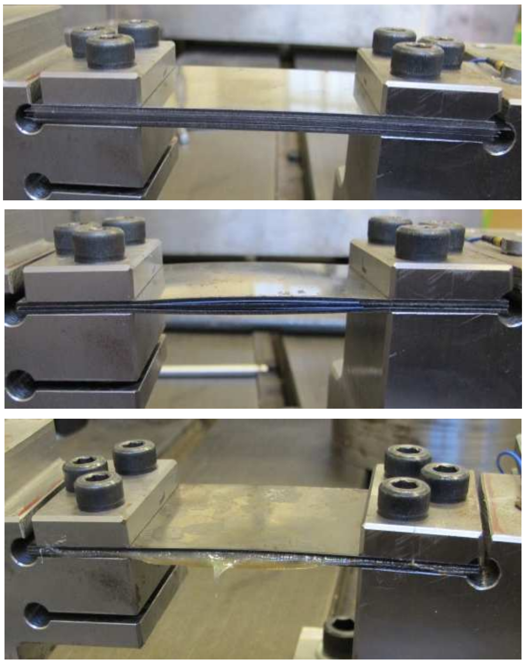

Fig. 6. Examples of sandwiches (PVC, paper, grease)

3.2. Test results

Using these experimental tests, the most suitable composition of the sandwich was identified and thus the natural frequency of the experimental device for tool oscillation outside its working range was increased.

A slight influence of the grip type can be observed in Fig. 7. In this case the single plate springs of 3.5 mm and 4.5 mm thickness bolted in both types of grips were measured.

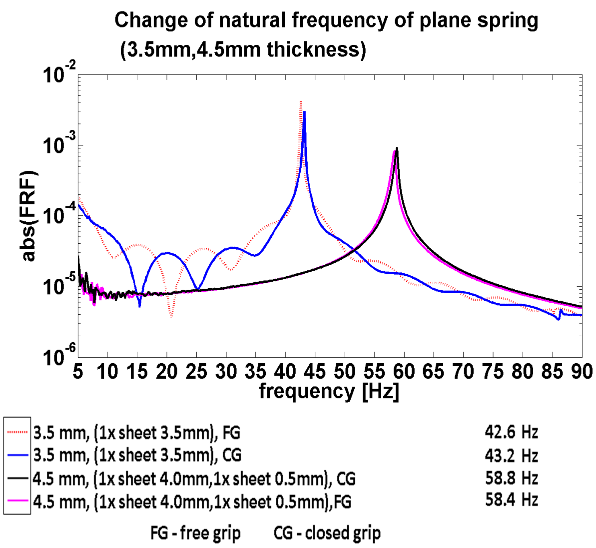

Fig. 7. Influence of the grip type

The difference in the natural frequencies and damping is very small. The free grip type is more suitable for our purposes due to the possibility of clamping higher thickness of plate and in consequence better damping of the whole sandwich (to be discussed in the next paragraphs). Of course, by increasing the plate thickness, the natural frequency rises.

If we compare sandwiches composed from 1.0 mm sheet metal and a damping interlayer, as can be seen in Fig. 8, we can conclude that 1) by increasing the number of sheet metals the natural frequency rises (owing to higher absolute thickness), 2) more interlayers lead to better damping of the sandwich. If the sandwich is composed of thicker metal sheets, the final natural frequency will be higher, compared with the variant of the same thickness but composed of a higher number of metal sheets.

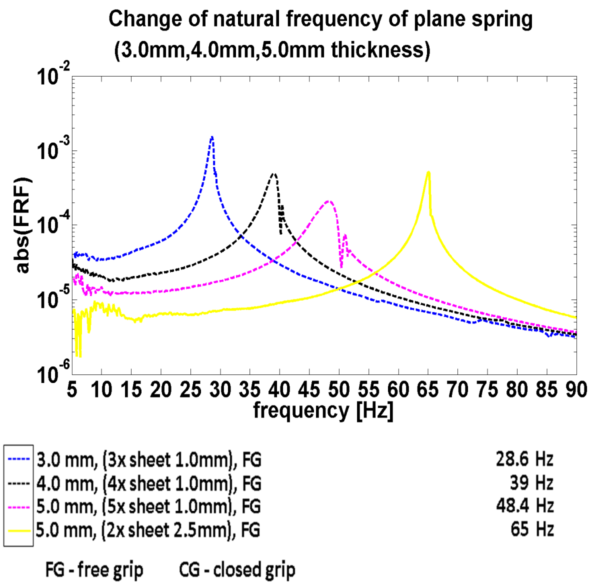

Fig. 8. Influence of the number of damping interlayers

The influence of various interlayer types on damping and natural frequency shift is summarised in Fig. 9. Using the PU glue helps only very slightly as well as using the grease layer between the metal sheets. If we consider a pure sandwich without damping interlayers, natural frequency is always slightly lower. Adding interlayers raises sandwich thickness and thus natural frequency. The paper interlayer gives better results than PVC. Especially a thin layer of PVC caused lower natural frequency; damping was only slightly different. If we focus on the sandwich composed of sheet metal and paper, using paper of square shape (variant V7, see Fig. 5 and Fig. 6), we obtain better damping but more nonlinearity in FRF. Thus we recommend using interlayers of the same shape as plate springs.

These results can be confirmed by analysing the measurement done for the sandwich of a nominal thickness of 5.0 mm; see Fig. 12 in Appendix A. All the realized tests are summarized here and divided into three graphs based on the nominal thickness of the sandwich.

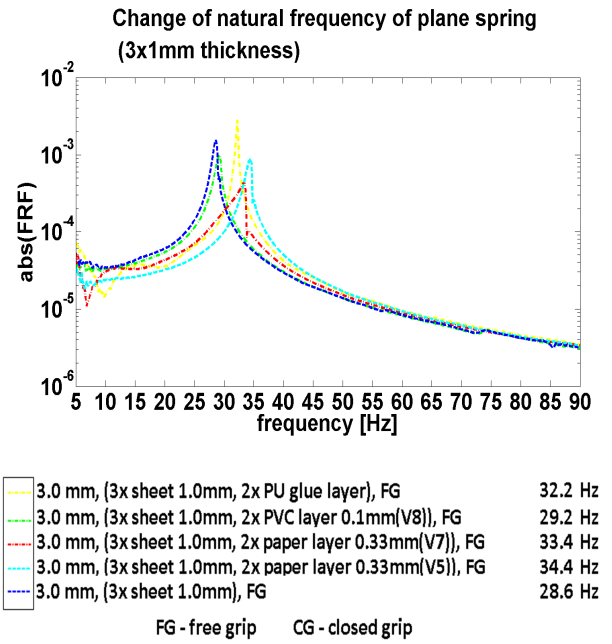

Fig. 9. Influence of the interlayer type

4. CONCLUSIONS

This paper reports on the design of an experimental device for tool oscillation in the cut and on an adjustment of its dynamic properties. Based on an experiment, a composition of a sandwich from steel plate springs and paper interlayers was optimized so that the natural frequency of the experimental device for tool oscillation would not reach its working range. It was shown, that by choosing of appropriate sandwich composition dynamic properties could be tuned effectively.

A sandwich from four sheet metals with a thickness of 1.0mm and one sheet metal with a thickness of 0.5mm with paper interlayers with a thickness of 0.18mm was identified as the most suitable for the given configuration. All layers were bolted together on the edge of the sandwich in the free grip.

Following the above-mentioned tuning of the dynamic properties, further tests of the functionality of the redesigned experimental device for tool oscillation on the machine were successfully run. The implementation in experiment can be seen in the Appendix B.

ACKNOWLEDGMENTS

This research is supported in the framework of the grant Competence Centres, TE01020075– Production technology, of the Technology Agency of the Czech Republic.

REFERENCES

[1] M. Poláček, *Calculation of Machine Tool Structure Stability against Self-excited Vibrations (in Czech)*, Ph.D. Thesis, CTU in Prague, The faculty of mechanical engineering, 1955.

[2] M. Poláček, *Method of dynamic coefficient of a cutting force measurement*, Research report (in Czech) No. V 2142, VÚOSO in Prague, 1969.

[3] J. Peters, et al., *The Measurement of the Dynamic Cutting Coefficient*, CIRP Annals, 2, 21, 1972.

[4] J. Tlusty, *Analysis of the Research in Cutting Dynamics*, Annals of the CIRP, 2, 27, p. 583-589, 1978.

[5] B. S. Goel, *Measurement of Dynamic Cutting Force Coefficients, A* Thesis for the Degree of Ph. D., Hamilton, McMaster University, 1976.

[6] S. B. Rao, *Analysis of Dynamic Cutting Force Coefficient*, A Thesis for the Degree of Ph. D., Hamilton, McMaster University, 1977.

[7] J. Tlusty, et al., *The Dynamic Cutting Coefficient for Some Carbon Steels*, Proc. 4th NAMR Conf., Battelle's Labs, Columbus, 1976.

[8] P. Bach, M. Poláček, P. Chvojka, J. Drobílek, *Comparative Analysis of Lower Speed Chatter Behaviour*, MM Science Journal, No. 12. ISSN 1212-2572. Available: http://www.mmscience.eu/201314, 2013.

[9] P. Bach, *Vibration in Machining (in Czech)*, Machining&Tooling, 3/12, s. 1-5, 2012.

[10] P. Bach, M. Poláček, P. Chvojka, J. Drobílek, *Dynamic Forces in Unstable Cutting during Turning Operations*, Manufacturing technology, Vol. 14, No. 1, UJEP, FPTM, Ústí n. L., s. 3 – 8, 2014.

APENDIX A

The complete results of the tests see to next figures. For better orientation all the results are divided into three graphs (Fig. 5, 6 and 7.) based on plate spring thickness. The legend below the figures provides the thickness of sandwich components and sandwich composition as well as the appropriate measured natural frequency.

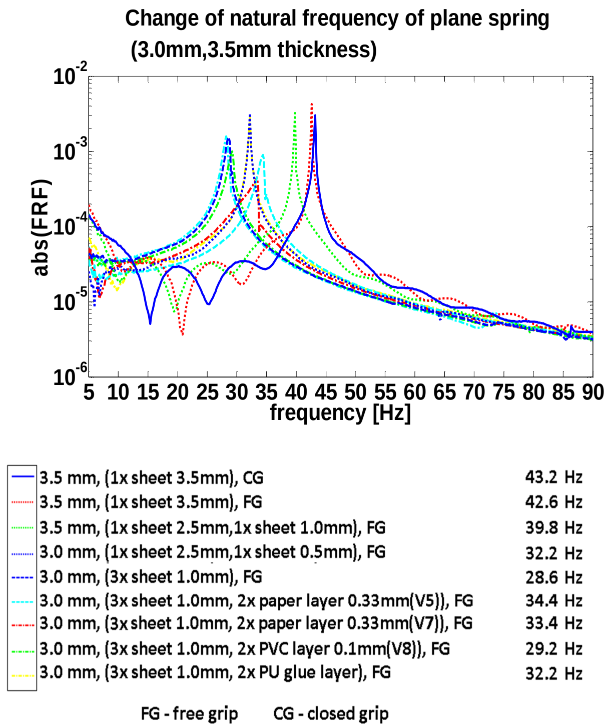

Fig. 10. Results of the FRF measurements thickness 3.5mm

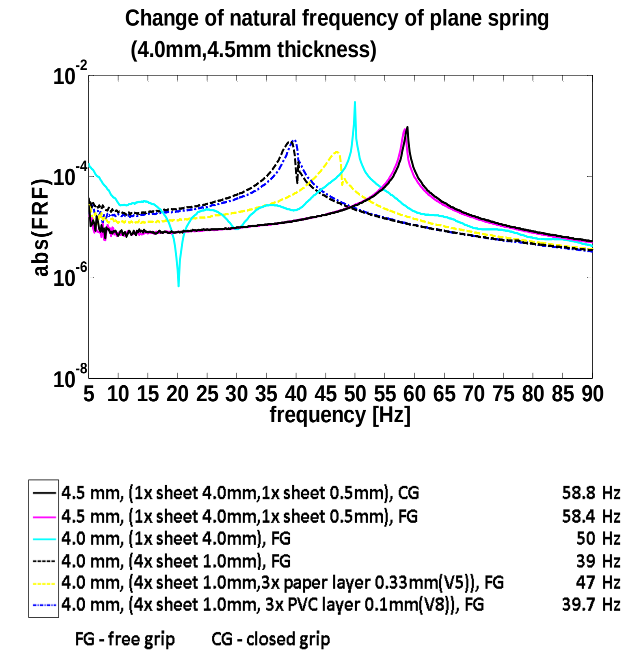

Fig. 11. Results of the FRF measurements thickness 4mm and 4.5mm

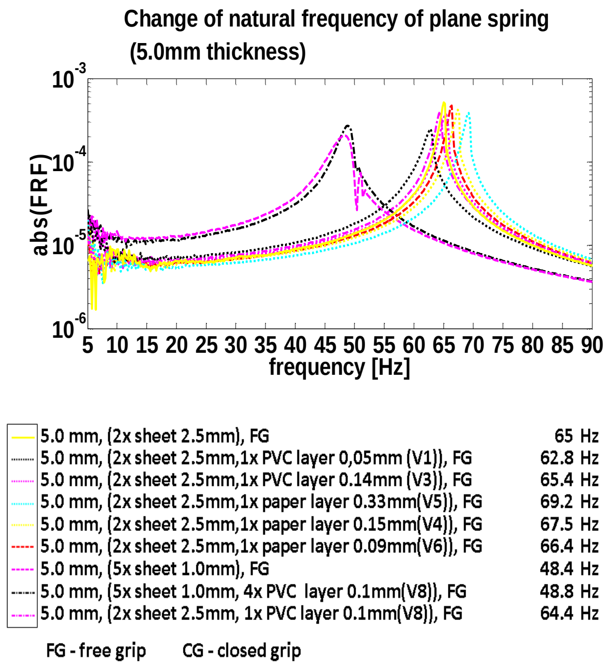

Fig. 12. Results of the FRF measurements thickness 5mm

APENDIX B

After the dynamic properties of the experimental device had been adjusted, tests of tool oscillation on the machine were run based on the method shown in Fig. 1 in the paper. The clamping of the experimental device in the turret is shown in Fig. 13. For the detail of sensor placement see Fig. 14.

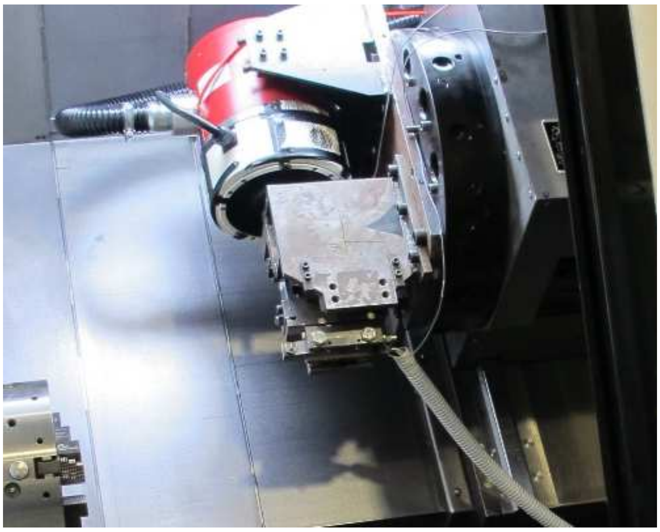

Fig. 13. Device installed on the machine tool

Final composition of the sandwich used in the experimental device in Fig. 14. – see the red circle.

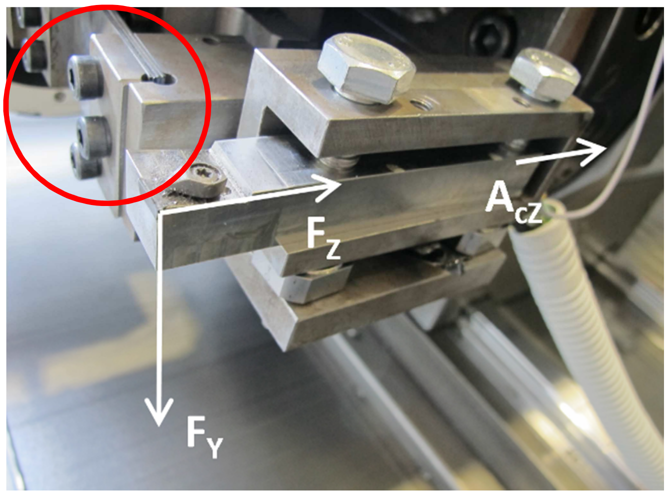

Fig. 14. Cutting tool with sensors