Applied Computer Science, vol. 13, no. 1, pp. 75–84
doi: 10.23743/acs-2017-07

Submitted: 2017-01-20
Revised: 2017-03-01
Accepted: 2017-03-18

modal analysis, stability, milling process, surface roughness

Paweł PIEŚKO[*], *Magdalena ZAWADA-MICHAŁOWSKA*[*]

USEFULNESS OF MODAL ANALYSIS FOR EVALUATION OF MILLING PROCESS STABILITY

Abstract

The paper presents evaluation of modal analysis usefulness for determination of milling process stability. In the first phase of the study experimental modal analysis was performed and using CutPro 9.5 software, stability lobes were generated. In the next step, machining tests were carried out. The last stage of the experiment involved verification of modal analysis usefulness for evaluation of milling process stability based on surface roughness measurements. Conducted research allowed to state that modal analysis can be a useful tool for determining milling process stability.

1. INTRODUCTION

Machining is one of the fastest growing methods of manufacturing. Effective type of cutting is milling where it is necessary to determine the appropriate process conditions, ensuring its stable course. The stability of process is significant mainly in the context of obtaining maximum machining capability as well as avoidance of surface quality deterioration, resulting from vibrations of both the tool and the workpiece (particularly during cutting of thin-walled elements). Additionally, they generate accelerated wear of cutting tools and high-frequency noise (Bojanowski & Pawłowski, 2011; Budak, Tunc, Alan & Ozguven, 2012; Campa, de Lacalle & Celaya, 2011; Sun & Xiong, 2017).

[*]Department of Production Engineering, Lublin University of Technology, Nadbystrzycka Street 36, 20-618 Lublin, Poland, e-mail: m.michalowska@pollub.pl, p.piesko@pollub.pl

Milling process stability is understood as a condition wherein self-excited vibrations do not occur or emerging oscillation is extinguished. This phenomenon is very complex and it depends on many factors. The most important of them are presented in Fig. 1 (Kilic & Altintas, 2016; Maamar, Bouzgarrou, Gagnol & Fathallah, 2017; Płodzień & Żyłka, 2013).

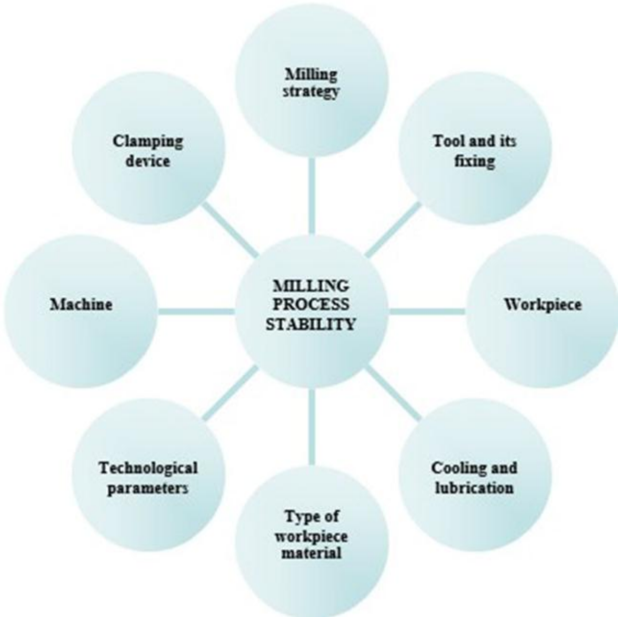

Fig. 1. Factors affecting milling process stability (Płodzień & Żyłka, 2013)

Recently a dynamic development of issues related to machining stability has been observed. Currently, the appropriate definition of process condition, ensuring its stable course and avoidance vibrations is possible by using specialized software (e.g.: ShopPro, CutPro) that allows the selection of optimal technological parameters (Płodzień & Żyłka, 2013; Totis, Albertelli, Sortino & Monno, 2014).

The most widely used stability forecasting method of OUPN system (machine-clamping-workpiece-tool) is to determine stability lobes for settled process conditions. Stability lobes present the dependence of rotation speed n usually in function of depth of cut a_p (or width of cut a_e) defining stable and unstable areas. Experimental modal analysis is used for obtaining these curves (Totis et al., 2014; Totis, Albertelli, Torta, Sortino & Monno, 2017; Zhang, Xiong, Ding, Feng & Xiong, 2012).

The issue with OUPN system during milling proceeds mainly from the intermittent work of mill, causing the periodic tool deflection from the workpiece. As a result of this, corrugated structure is formed on work surface after the pass of cutting tool. To sum up, if frequency of entering blade is not equal to frequency of natural vibrations, phase displacement is formed between the tool and the workpiece. Consequently, the effect is a variable value of width of cut layer h, resulting in various cutting forces and generating negative self-excited vibrations (Ahmadi & Ismail, 2012; Ciurana & Quintana, 2011; Lehrich & Lis, 2014; Twardowski, 2006; Zhang et al., 2012).

2. METHODOLOGY

The aim of the study was to evaluate modal analysis usefulness for determination of milling process stability. In the first stage of the study, modal analysis was carried out and based on stability lobes, technological parameters corresponding to stable and unstable ranges of tool work were read. On the grounds of the obtained results, machining tests were made. Then, the verification of modal analysis usefulness for determination of milling process stability was performed, based on surface roughness measurements.

The study was conducted on vertical machining centre AVIA VMC 800 HS with application of set for modal analysis (Fig. 2), where main elements were: modal hammer with force measurement sensor, accelerometer, data acquisition module and a computer with CutPro 9.5 software, among others.

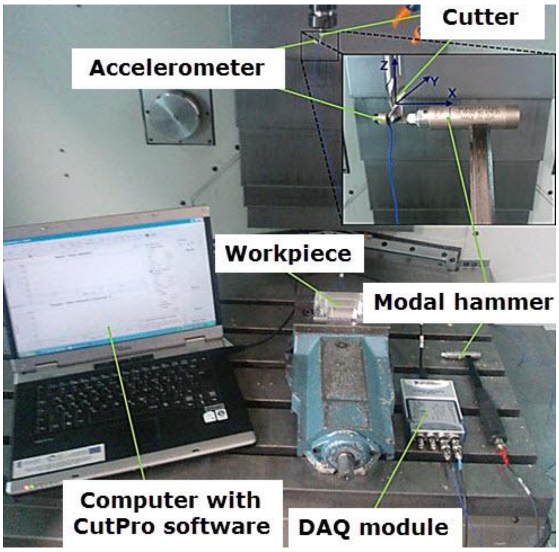

Fig. 2. Set for modal analysis (own study)

Constant technological parameters were defined in CutPro 9.5 program, i.e.: width of cut a_e = 1 mm and feed per tooth f_z = 0.04 mm/tooth, properties of workpiece material and tools geometry.

Aluminum alloy EN AW-2024 T351 (chemical symbol: EN AW-AlCu4Mg1) that is widely applied in industry, especially aerospace, was used for the study. Its chemical composition and selected properties are presented in Table. 1.

Tab. 1. Chemical composition and selected properties of alloy EN AW-2024 (PN-EN 573-3:2014-02; PN-EN 485-2:2016-10)

<table>
<tr><td rowspan="2">Chemical composition</td><td>Si</td><td>Fe</td><td>Cu</td><td>Mn</td><td>Mg</td><td>Cr</td><td>Zn</td><td>Ti</td></tr>
<tr><td>0.5</td><td>0.5</td><td>3.8 – 4.9</td><td>0.3 – 0.9</td><td>1.2 – 1.8</td><td>0.1</td><td>0.25</td><td>0.15</td></tr>
<tr><td rowspan="2">Properties</td><td colspan="2">Density, ρ</td><td colspan="2">Young's modulus, E</td><td colspan="2">Tensile strength, R_m</td><td colspan="2">Yield strength, $R_{p0,2}$</td></tr>
<tr><td colspan="2">2.78 g/cm^3</td><td colspan="2">73 GPa</td><td colspan="2">430 MPa</td><td colspan="2">290 MPa</td></tr>
</table>

Two solid end mills destined for aluminium alloys machining were used in the experiment:

- Seger (PUN-12-00-24/50-100-3AL),
- SGS Solid Carbide Tools (44748).

Mill of Seger (PUN-12-00-24/50-100-3AL) that was made on special order is shown in Fig. 1, and Table 2 presents its technical specifications.

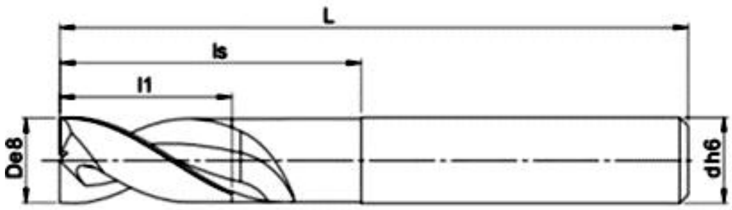

Fig. 3. Mill of Seger PUN-12-00-24/50-100-3AL ("Seger online catalog", 2016)

Tab. 2. Technical data of Seger mill PUN-12-00-24/50-100-3AL ("Seger online catalog", 2016)

Symbol:	PUN-12-00-24/50-100-3AL
Number of milling inserts z:	3
Cutting diameter D [mm]:	12
Overall length L [mm]:	100
Length of cut l_1 (a_p) [mm]:	50
Shrank diameter d [mm]:	12

Mill of SGS Solid Carbide Tools (44748) destined for high performance machining is presented in Fig. 4. Its technical parameters are shown in Table. 3.

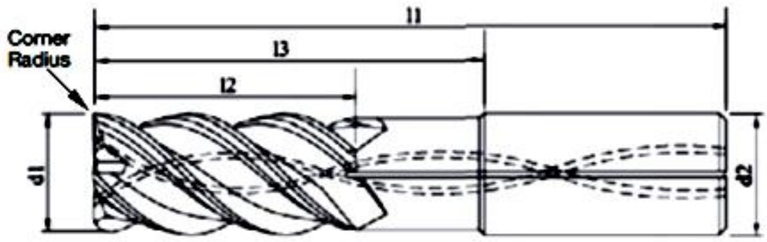

Fig. 4. Mill of SGS Solid Carbide Tools 44748 ("SGS online catalog", 2016)

Tab. 3. Technical data of SGS Solid Carbide Tools mill 44748 ("SGS online catalog", 2016)

Symbol:	44748
Number of flutes z:	4
Cutting diameter d_1 [mm]:	12
Length of cut l_2 (a_p) [mm]:	48
Overall length l_1 [mm]:	100
Shrank diameter d_2 [mm]:	12
Corner radius R [mm]:	2

Machining tests were carried out with technological parameters corresponding to stable and unstable ranges of work:

- for mill of Seger:
  - parameters of stable work:
    - n = 19 700 rpm,
    - a_p = 20 mm,
  - parameters of unstable work:
    - n = 12 800 rpm,
    - a_p = 20 mm,
- for mill of SGS:
  - parameters of stable work:
    - n = 20 400 rpm,
    - a_p = 15 mm,
  - parameters of unstable work:
    - n = 14 400 rpm,
    - a_p = 15 mm.

The cuboidal samples were machined during milling. They were mounted in a vice as is presented in Fig. 5.

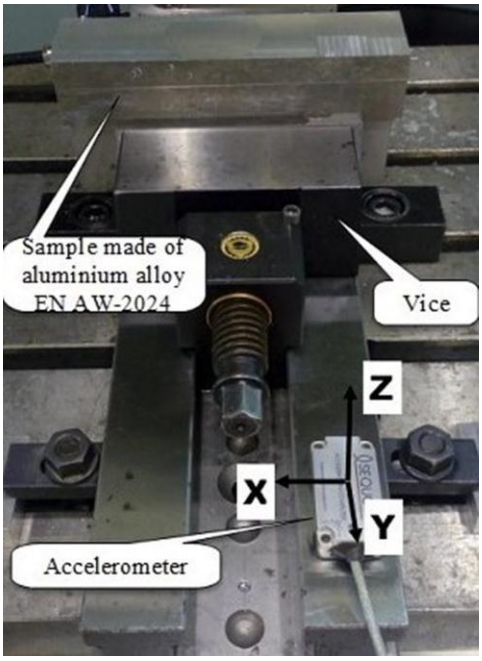

Fig. 5. Method of sample fixing

Surface quality was adopted as a criterion for evaluation of milling process stability. For this purpose, parameter Ra was measured by using a contact profilometer – Hommel Tester T1000 (Fig. 6).

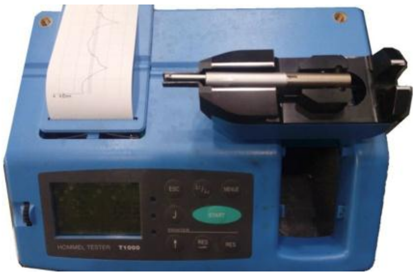

Fig. 6. Hommel Tester T1000 profilometer

Measurements of surface roughness were repeated five times for each tested tool.

3. RESULTS

Based on the collected signals and defined parameters, stability lobes were generated by means of CutPro software. These charts were used for the determination of stable and unstable areas.

The obtained graphs were modified by adding the values of technological parameters for machining tests:

– stable work – green colour,
– unstable work – red colour.

The obtained stability lobes for mill of Seger is presented in Fig. 7 and Fig. 8 for mill of SGS.

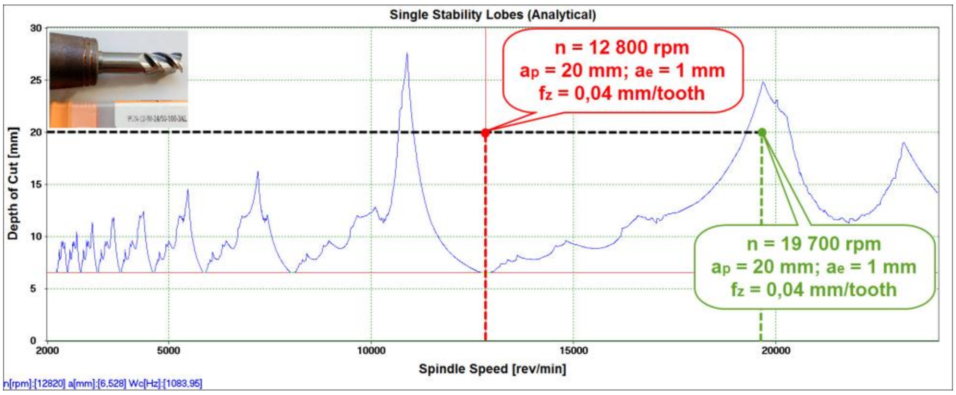

Fig. 7. Obtained stability lobes for mill of Seger

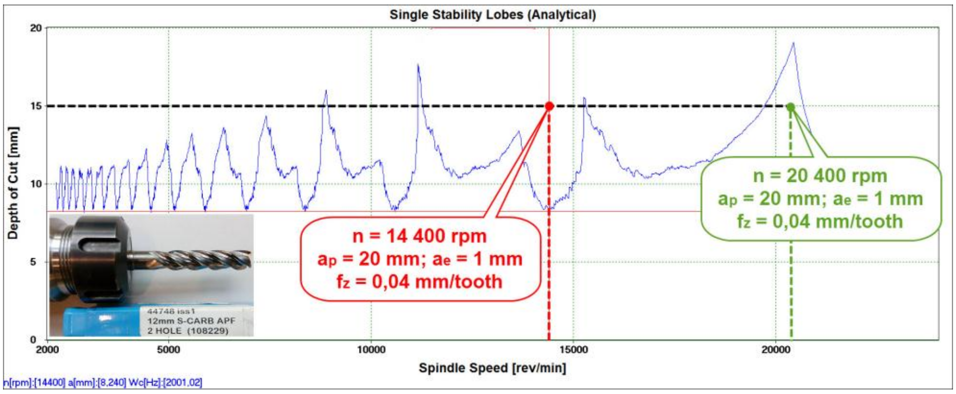

Fig. 8. Obtained stability lobes for mill of SGS (own study)

The range of stable tool work corresponds to the areas that are located under stability lobes. Based on graphs, the existence of liminal depth of cut a_p is noted below where theoretically machining is stable, regardless of cutting speed v_c. The characteristic increase of width range of stable and unstable areas with growth of rotation speed n is also visible. It facilitates the selection of machining parameters (rotation speed n), to ensure that they are located in the range of stable or unstable machining, therefore, the highest values of rotation speed n were selected for the verification. Additionally, the points corresponding to the central positions of both stable and unstable areas were taken.

Another phase of study was the verification of modal analysis usefulness for determination of milling process stability based on surface roughness measurements. The values of Ra surface roughness parameter for examined mills and technological parameters corresponding to stable and unstable machining are shown in Fig. 9.

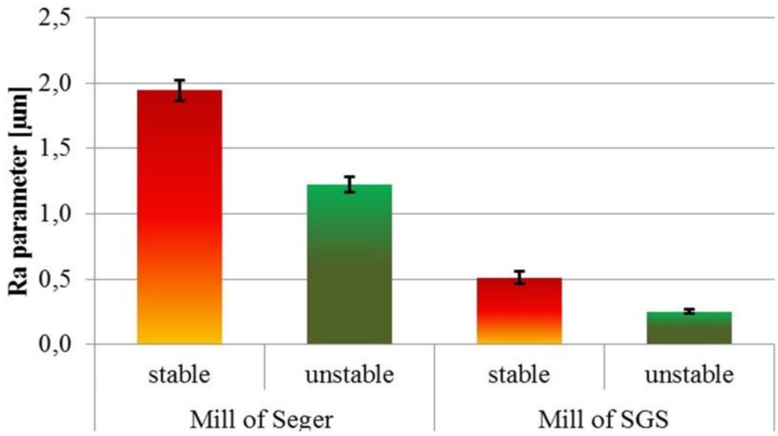

Fig. 9. The values of Ra surface roughness parameter for two tested mills and technological parameters corresponding to stable and unstable machining

With regard to graph (Fig. 9) the green columns present the obtained roughness values which according to the results of modal analysis corresponding to machining parameters ensure stable work. Unstable conditions were marked with red colour. The higher values of Ra parameter were obtained for unstable conditions of machining for both mills.

4. CONCLUSION

The conducted analysis allowed to formulate following conclusions:

- On graphs generated from CutPro software, the existence of liminal depth of cut a_p has been noted, where theoretically machining is stable, regardless of rotation speed n.

- The characteristic increase of width range of stable and unstable areas with growth of rotation speed n has been also visible.
- The higher values of Ra parameter were obtained for unstable conditions of machining for both cases.
- The performed verification allows to state that experimental modal analysis using CutPro software can be a useful tool for evaluation of milling process stability.
- The results of modal analysis help to determine machining ensuring required machining quality.

REFERENCES

Ahmadi, K., & Ismail, F. (2012). Stability lobes in milling including process damping and utilizing Multi-Frequency and Semi-Discretization Methods. *International Journal of Machine Tools & Manufacture*, *54-55*, 46–54. doi:10.1016/j.ijmachtools.2011.11.007

Bojanowski, S., & Pawłowski, W. (2011). Teoretyczna analiza modalna zespołu wrzeciennika przedmiotu szlifierki do otworów. *Mechanik*, *84*(11), 870-873.

Budak, E., Tunc, L. T., Alan, S., & Ozguven, H. N. (2012). Prediction of workpiece dynamics and its effects on chatter stability in milling. *CIRP Annals-Manufacturing Technology, 61*(1), 339–342. doi:10.1016/j.cirp.2012.03.144

Campa, F. J., de Lacalle, L. N. L., & Celaya, A. (2011). Chatter avoidance in the milling of thin floors with bull-nose end mills: Model and stability diagrams. *International Journal of Machine Tools & Manufacture, 51*(1), 43–53. doi:10.1016/j.ijmachtools.2010.09.008

Ciurana, J. & Quintana, G. (2011). Chatter in machining processes: A review. *International Journal of Machine Tools and Manufacture*, *51*(5), 363–376. doi:10.1016/j.ijmachtools.2011.01.001

Kilic, Z. M., & Altintas, Y. (2016). Generalized mechanics and dynamics of metal cutting operations for unified simulations. *International Journal of Machine Tools & Manufacture, 104*, 1–13. doi:10.1016/j.ijmachtools.2016.01.006

Lehrich, K., & Lis, K. (2014). Analiza modalna korpusu stojaka obrabiarki CNC. *Inżynieria Maszyn*, *19*(1), 20-33.

Maamar, A., Bouzgarrou, B. C., Gagnol, V., & Fathallah, R. (2017). Time Domain Stability Analysis for Machining Processes. *Advances in Acoustics and Vibration, 5*, 77–88. doi:10.1007/978-3-319-41459-1_8

Płodzień, M., & Żyłka, Ł. (2013). Stabilność 5-osiowego frezowania stopów aluminium. *Mechanik*, *86*(2), 1–12.

Polish Norm: PN-EN 485-2:2016-10. Aluminium and aluminium alloys. Sheet, strip and plate. Part 2: Mechanical properties.

Polish Norm: PN-EN 573-3:2014-02. Aluminium and aluminium alloys. Chemical composition and form of wrought products. Part 3: Chemical composition and form of products.

Seger online catalog. (n.d.). Retrieved November 30, 2016, from Seger website, http://www.seger.net.pl/pl

SGS online catalog. (n.d.). Retrieved November 30, 2016, from SGS Solid Carbide Tools website, http://sgstool.com

Sun, Y., & Xiong, Z. (2017). High-order full-discretization method using Lagrange interpolation for stability analysis of turning processes with stiffness variation. *Journal of Sound and Vibration*, *386*, 50–64. doi:10.1016/j.jsv.2016.08.039

Totis, G., Albertelli, P., Sortino, M., & Monno, M. (2014). Efficient evaluation of Process stability in milling with Spindle Speed Variation by using the Chebyshev Collocation Method. *Journal of Sound and Vibration, 333*(3), 646–668. doi:10.1016/j.jsv.2013.09.043

Totis, G., Albertelli, P., Torta, M., Sortino, M., & Monno, M. (2017). Upgraded stability analysis of milling operations by means of advanced modeling of tooling system bending. *International Journal of Machine Tools & Manufacture*, *113*, 19–34. doi:10.1016/j.ijmachtools.2016.11.005

Twardowski, P. (2006). Stabilność procesu frezowania stali na twardo w warunkach HSM. *Archiwum Technologii Maszyn i Automatyzacji*, *26*(2), 93–101.

Zhang, X. J., Xiong, C. H., Ding, Y., Feng, M. J., & Xiong, Y. L. (2012). Milling stability analysis with simultaneously considering the structural mode coupling effect and regenerative effect. *International Journal of Machine Tools & Manufacture*, *53*(1), 127–140. doi:10.1016/j.ijmachtools.2011.10.004