Experimental Study of the Effect of Variable Pitch in Indexable Cutting Tool on AISI4140 Steel Surface Finish in Milling

Behrouz MahdiKhani [1]
Department of Mechatronics Engineering,
South Tehran Branch, Islamic Azad University, Tehran, Iran
Tehran, Iran Email: behrouzmahdikhani@yahoo.com

Mehrdad Javadi [2, *]
Department of Mechatronics Engineering,
South Tehran Branch, Islamic Azad University, Tehran, Iran
Email: Mjavad@azad.ac.ir
*Corresponding author

Received: 10 January 2020, Revised: 24 April 2020, Accepted: 5 May 2020

Abstract: Chatter is one of the most limitations that cause undesirable effect on improving productivity and part quality. In this paper, an experimental method has been used for analysing the effect of changing pitch in the indexable cutting tool in milling. For this purpose, the cutting forces of machining in three different directions were investigated and a comparison was made between tools with equal and unequal pitches. Milling of AISI 4140 has been performed with two different depths of cut (0.5&1mm) and the machining surface finish were examined. Furthermore, by using accelerometer sensors, the machining vibrations and machining forces by using dynamometer were measured. According to the findings, as well as the reduction of vibrations of machining about 50 %, machining forces reduction between 15% and 30% and surface finish improvement more than 200%were observed. In this regard, utilizing tools with different pitches leads to improvement in machining efficiency, reducing energy consumption, manufacture of high quality parts and it will ultimately reduce costs.

Keywords: Machining Efficiency, Milling, Chatter Phenomenon, Tools with Different Pitch

Reference: Behrouz MahdiKhani, Mehrdad Javadi, "Experimental Study of the Effect of variable Pitch in Indexable Cutting Tool on AISI4140 Steel surface finish in Milling", Int J of Advanced Design and Manufacturing Technology, Vol. 13/No. 3, 2020, pp. 99–105. DOI: 10.30495/admt.2020.1890458.1166.

Biographical notes: Behrouz Mahdikhani is currently the Head of Mechanical Engineering Department and R&D of machining tools of Taban Gostar Pooya Co. He Received his MSc degree in Mechanical Engineering from University of IAU, South Tehran Branch, in 2019. His expertise is machining tools and heat treating. **Mehrdad Javadi** is an associate professor of Mechanical engineering at the Islamic Azad University, South Tehran Branch. Tehran, Iran. He received his BSc in Mechanical engineering from Sharif University of Technology and MSc from Tehran University. He received his PhD from Islamic Azad University, Science and Research Branch. His expertise is Mechanical design, Flexible Manufacturing Systems and Mechatronics engineering application. Also He has worked on topics concerning metal forming application.

1 INTRODUCTION

Machining vibrations known as chatter phenomenon will take place by dynamic contact of tools with the work piece and cutting forces movement during machining by tools. This phenomenon can also happen at low speeds of machining. In order to remove the effect of chatter, further operations for improvement of surface finish should be done in this regard. Thus, chatter can cause production efficiency reduction, increase cost, and decrease product quality.

In the last 50 years, many models have been developed and used for milling process [1]. One of the best models for determining the chatter's area is stability lobe diagrams. In the Stability Lobe Diagram (SLD), the stable and unstable areas are separated by the graph of a critical cutting parameter plotted against the spindle speed. Large chatter-free depth of cuts is usually available for high cutting speeds which may not be possible to be attained for some processes due to material of workpiece and machine tool limitations. High-temperature alloys used in aerospace industries such as titanium and nickel are common examples. Variable pitch cutters, on the other hand, can be used to suppress chatter in those cases.

Using milling tools with unequal pitch angle is effective for high and low-speed machining. To design the tool with a variable pitch angle, the pitch angle must be selected accurately. E. Budak suggested an analytical method for choosing pitch angle in end mill tools [2] and showed the effect of unequal pitch on production efficiency by using dynamometer and acoustic measurement. He also showed that chatter stability can be improved even at slow cutting speed by designing the pitch angles properly [3].

Sims studied on variable helix milling tools. He recommended a mathematical model for decreasing chatter. He also suggested that whilst variable helix tools can have more operating regions that are stable, multi-frequency behaviour and non-linear cutting stiffness behaviour can have a critical influence on the accuracy of model predictions [4]. Young wang and colleagues suggested a numeric model for tools with different pitch and variable helix and concluded that using tools with different pitch and helix, can remove chatter. Young wang also has showed that variable pitch and variable helix milling can obtain larger stable cutting area in comparison to uniform pitch and uniform helix milling [5].

Otto drove a numerical method for non-uniform pitch and variable helix tools and got good coincide between the numerical and experimental results. He also revealed a significant increase of the limiting depth of cut for variable helix tool compared to the conventional tool [6]. Suzuki also proposed a novel design method of irregular pitch cutters, which ensures the simultaneous suppression of multi-mode regenerations [7]. Zatarain introduced a method called subspace iteration with good agreement in low order lobes region and better agreement in high order lobes [8].

Iglesias showed a method for definition of the optimum pitch angels between inserts in face mill and got remarkable results like improving material removal up to three times [9]. Innovation of this paper is the study of effect of the unequal pitch angle in milling operation with indexable face milling tools at the same time as the mass balance and also measurement of forces and vibrations in three directions and surface quality.

2 STABILITY LOBES OF CUTTERS

In milling, one of the structural modes of the machine tool-workpiece system is excited by cutting forces initially. The self-excited cutting system becomes unstable, and chatter vibrations grow until the tool jumps out of the cut or breaks under the excessive cutting forces. This phenomenon that is called chatter is the most important factor for limiting material removal rates and also causes uneven surface, "Fig. 1". [10].

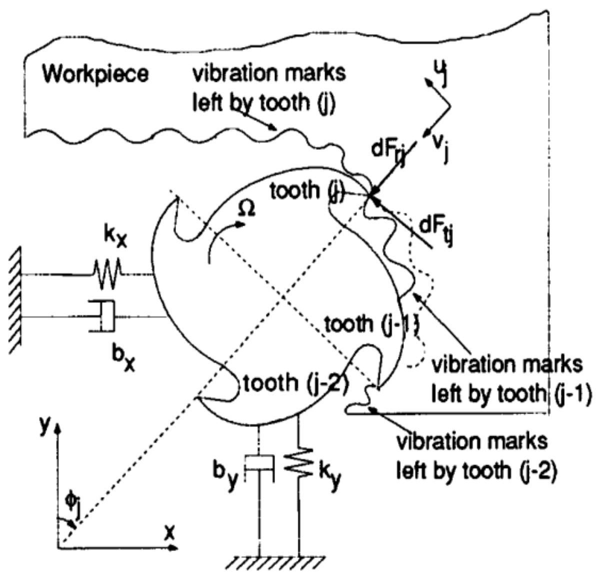

Fig. 1 The dynamic model of milling tools with 2 degrees of freedom [10].

When chatter happens, vibration amplitudes increase. One of the best methods for finding an area without chatter is using SLD diagram for that tool. In SLD diagram chatter happens in the higher area of the curve and lower area is a stable area. Norikazu Suzuki and et al. counted the SLD graph for some types of tools with a different pitch in a theoretical way ("Fig. 2") and they showed that using tools with unequal pitch can increase stable area [7]. The increasing stable area is related to choosing a suitable unequal pitch. The results of these calculations for unequal pitch angles in that research is shown in “Fig. 2”. In fact, the tool which has a more stable area is chosen as a tool with a suitable pitch angle. For example, tool with irregular pitch 3 and 4 in “Fig. 2” has the most stable area [7].

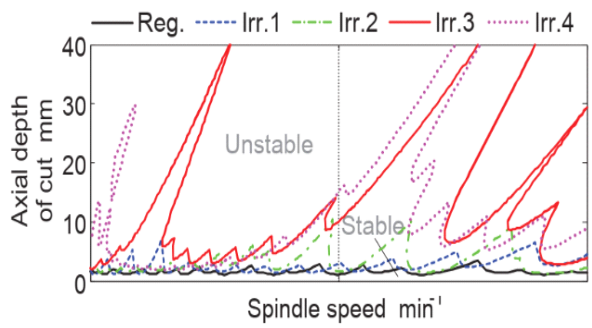

Fig. 2 Theoretical stability area [7].

Quintana Guillem and colleagues presented a new experimental methodology for identification of stability lobes diagram by utilizing taper sample at different speeds in milling operations. Where the workpiece permits a gradual increase of the axial depth of cut in the feed direction, which represents the Y coordinate of the SLD diagram while the spindle speed (X coordinate of the SLD) increased between passes.

In that method during milling test, chatter arises at certain combinations of the axial depth of cut and spindle speed. With a microphone, chatter is detected if the energy of the measured sound signal exceeds a certain threshold. The spindle speed is increased between passes in order to obtain combinations of spindle speed and axial depth of cut in the stability frontier and describe the SLD [11].

E. Buduk presents a model for choosing a suitable pitch by changing pitch angle linearly. This model is presented analytically for end mill tools. If ΔP be pitch angle variation in each constant P_0 and N is the number of cutting edges, the relation between the variation and the phase takes the following form:

$$\Delta P = \pi \frac{\Omega}{\omega_c} \quad \text{(Even N)} \quad \text{and} \quad \Delta P = \pi \frac{\Omega}{\omega_c} \frac{(N \pm 1)}{N} \quad \text{(Odd N)} \tag{1}$$

Where, Ω is the spindle speed (rad/sec), ω_c is chatter frequency that can be found by using sound analyzes, during machining. Pitch angle must be valid in Equation (2):

$$P_0 + (P_0 + \Delta P) + (P_0 + 2\Delta P) + \cdots + [P_0 + (\mathrm{N} - 1)\Delta P] = 2\pi \tag{2}$$

Based on Equation (2), P_0 can be expressed as follow:

$$P_0 = \frac{2\pi}{N} - \frac{(N-1)\Delta P}{2} \tag{3}$$

In this paper, pitch angles are designed in a way that the center of mass stays on the tool axis and do not cause unbalancing problems. In this type of pitch angles, the effect of variable pitch angles on surface finishing, cutting forces and vibrations will be studied experimentally in indexable face milling holders.

3 EXPERIMENTAL WORK METHOD

In order to investigate the effect of surface finishing with variable pitch angle in face milling holder proportional to tools with equal pitch angles, results of dynamometer and vibration measurement with accelerometer sensors and surface finishing results are used.

In “Fig. 3”, tools with equal and unequal pitch are shown. The tool has 6 pitches (cutting edges) and inserts used are XOMX12. The cutting diameter of the tool is 63 mm. As the spindle speed increases, unbalanced mass causes more damages to inserts. Therefore, the pitch angles are designed in a way that the center of mass stays on the tool axis (spindle) and do not cause unbalancing problems. So 6 pitch angles of tool respectively are: 65°,55°,65°,55°,65°, and 55°.

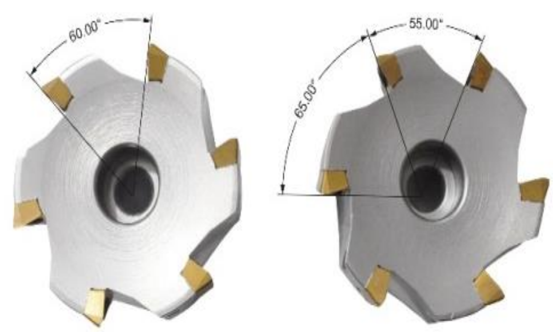

Fig. 3 Tool with equal and unequal pitches.

For testing forces in three directions, Kistler B9257 dynamometer and three axis CNC milling machine were used. According to these implements shown in “Fig. 4”, dynamometer has the ability to measure forces up to 10 KN. Three accelerometer sensors (AC102-1A) and DEWESOFT software are employed for analyzing the vibration. The sensors were installed in three different directions on the spindle. Image of three sensor’s connections are shown in “Fig. 5”, because vibration frequencies were about 1.3 KHz, based on Nyquist frequency, 20 KHz was chosen as the sampling rate.

Fig. 4 The milling machine and dynamometer that are used in the test.

Fig. 5 The testing system with vibration sensors.

Fig. 6 Sample 1-machining surface finish by the tool with unequal pitch; Sample 2-machining surface finish by the tool with equal pitch.

4 RESULTS AND DISCUSSION OF EXPERIMENTAL TESTS

At feed rate = 200 mm/min, spindle speed=700 rpm and depth of cut= 0.5 mm, results of surface finish (surface quality) for tools with unequal and equal pitch are according to the “Table 1”. The resulted surface after machining with two holders is shown at “Fig. 6”.

Table 1 Comparing the surface finish of two kind tools with unequal and equal pitch angle

Parameter	Unequal	Equal
R_a	1.47µm	3.35µm
R_z	7.80µm	17.08 µm
Rmax	8.20µm	23.67µm

Roughness profiles of two holders are shown in “Figs. 7, 8”. Based on the results of roughness profiles and “Table 1”, the surface finish by utilizing the tool with unequal pitch was better.

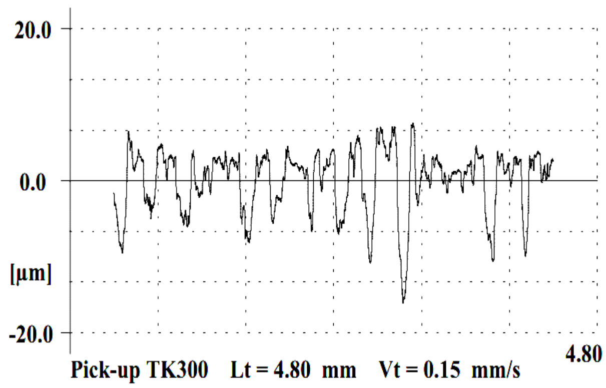

Fig. 7 Roughness profile for the tool with equal pitch.

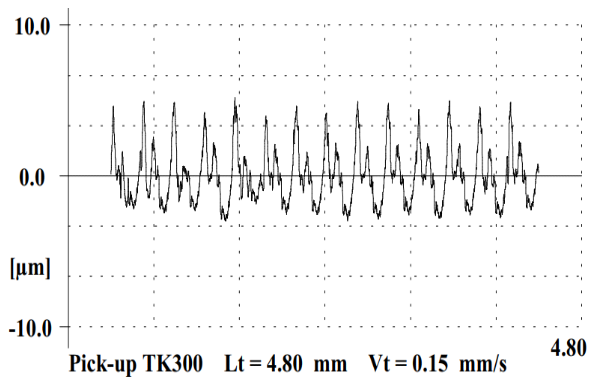

Fig. 8 Roughness profile for the tool with unequal pitch.

According to “Figs. 9-11”, results of measuring showed that cutting forces of machining by the unequal pitch, decrease in each direction of X, Y, and Z. Also, the amplitude of vibration was reduced.

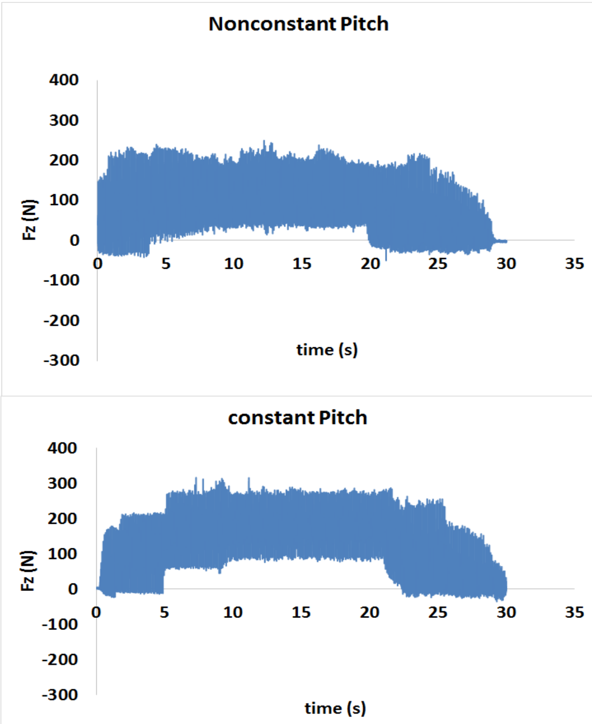

Fig. 9 Comparing forces in the Y direction of CNC milling machine in the state of the tools with unequal and equal pitch angle (S= 700 rpm, depth of cut= 0.5 mm and F= 200 mm/min).

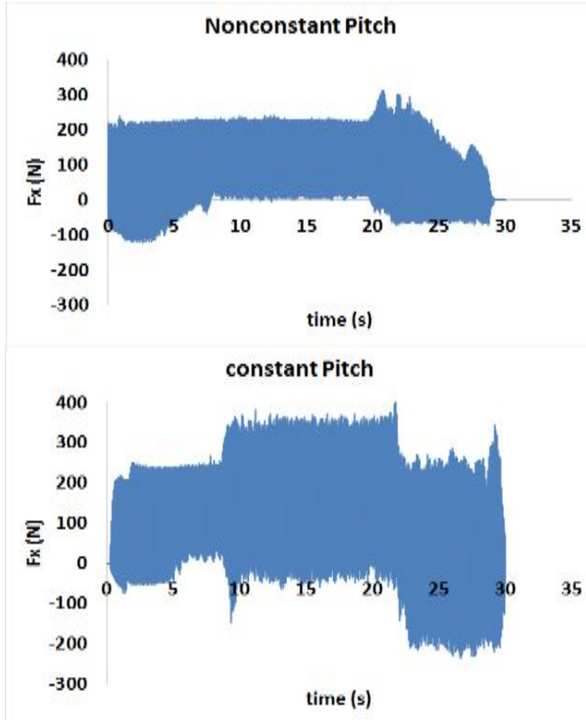

Fig. 11 Comparing forces in the Z direction of CNC milling machine in the state of the tools with unequal and equal pitch angle (S= 700 rpm, depth of cut= 0.5 mm and F= 200 mm/min).

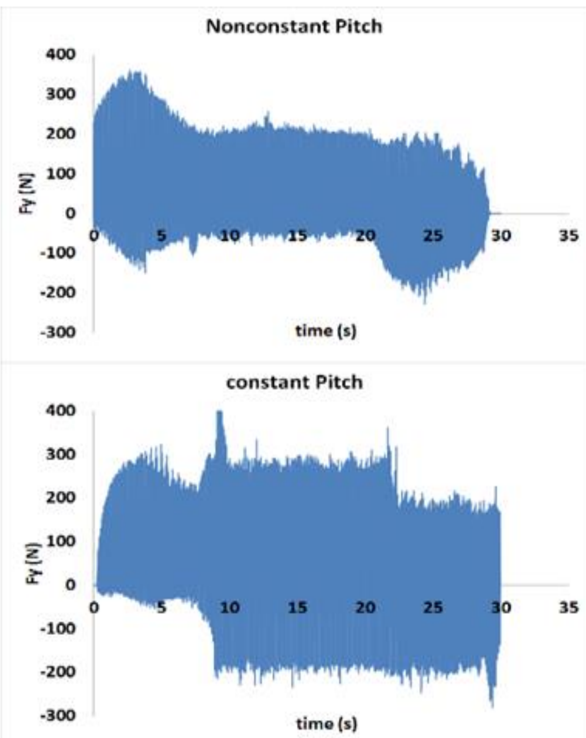

Fig. 10 Comparing forces in the X direction of CNC milling machine in the state of the tools with unequal and equal pitch angle (S= 700 rpm, depth of cut= 0.5 mm and F= 200 mm/min).

RMS criteria can be used for comparing graphs in terms of forces and vibration. Results of measuring forces with the dynamometer showed that the percentages of reducing forces in each direction are different. In general, machining forces reduced between 15% and 30%. For example, the RMS is equal to 111N in the feed direction, for machining forces in the state that the tool has equal pitch angles with the depth of cut= 0.5mm and for the tool with unequal pitch, it is 90N, which represents a 19% reduction.

For comparing the vibrational results of the accelerometer sensor, their RMS values are measured and the results are presented in “Table 2”.

Table 2 Results of vibration measurement with accelerometer sensors (Depth of cut= 2mm, F=350 mm/min, S=800 rpm)

	RMS	
Axes	Equal	Unequal
X	8.601	3.763
Y	6.176	2.478
Z	6.205	2.804
Average	6.994	3.015

Each sensor shows vibrations in one direction of machining. Y-axis is feed direction and Z axis is the tool axis. From the results presented in “Table 2”, it can be concluded that the vibration amplitude by using unequal pitch angle in the same condition gives fewer vibrations than half of the equal pitch angle vibrations. In “Figs. 12 and 13”, the vibrations at any time for both tools, are given in three directions. From these diagrams, it can also be concluded that after the tool-engagement with the workpiece, the vibration in all three directions for the tool with an unequal pitch has been reduced to less than half.

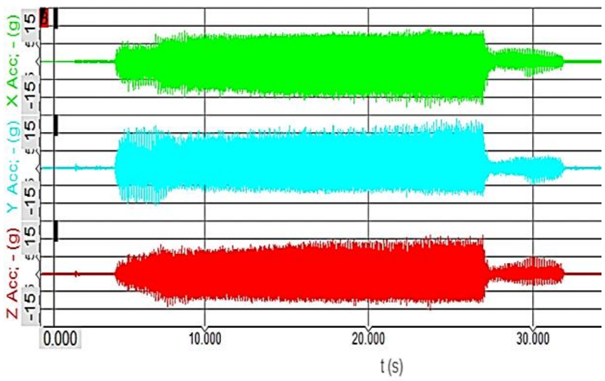

Fig. 12 Vibrations for the tool with unequal pitch.

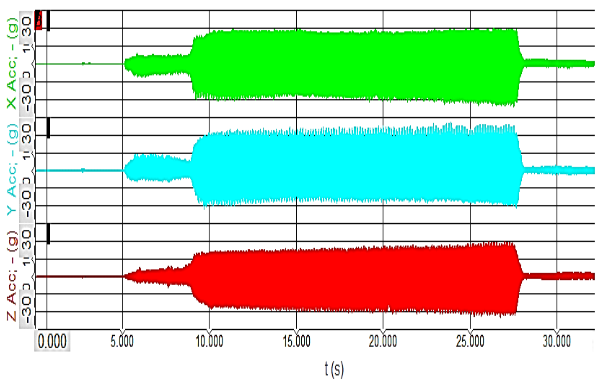

Fig. 13 Vibrations for the tool with equal pitch.

5 CONCLUSION

By using the tool with different pitch angles, the resonant vibrations produced by the cutting edges will vanish and the probability of the chatter will reduce. In the variable pitch angle tool, the cutting forces in all three directions, and the vibration amplitude decrease. Also, the results of surface finishing experiments showed that under similar conditions in different depth of cut, the tool with unequal pitch angle has better surface finishing. Therefore, it is possible to use variable pitch angle tool without occurrence chatter phenomenon and increasing machining efficiency. In summary, the results of comparing the surface roughness and vibration are presented in “Figs. 14 and 15”.

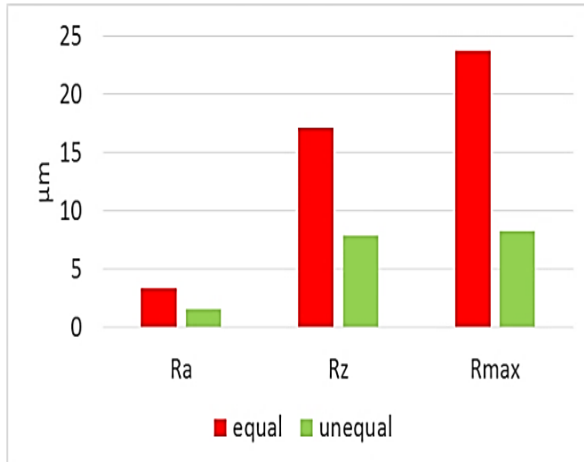

Fig. 14 Comparing surface roughness in equal and unequal pitch tools.

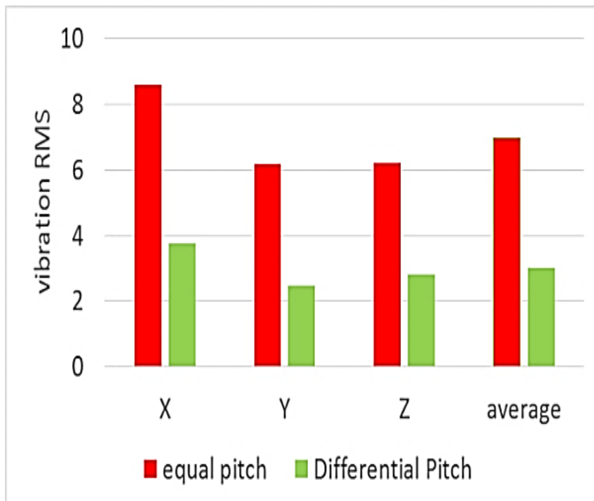

Fig. 15 Comparing machining vibration in 3 different directions.

In comparison to other articles which have studied on the variable pitch angles, there is remarkable coincidence between our results for example Budak [2-3] in theoretical aspect revealed that by using variable pitch angles we will have more stable area in SLD diagram which means using higher depth of cut and thereby higher productivity. Budak [3] also used linear increase in pitch angles which led into existing center of mass out of axial axis. So, in his theoretical method, he had eccentric effect which was solved in our method by using proper order of pitch angles.
Our result is also a confirmation of Wang research [5] which explain the result of using variable pitch angle and helix on preventing chatter and increasing efficiency.

6 ACKNOWLEDGMENTS

This project has been experimentally and financially supported by Taban Gostar Pooya Company.

REFERENCES

[1] Quintana, G., Ciurana, J., and Teixidor, D., A New Experimental Methodology for Identification of Stability Lobes Diagram in Milling Operations, International Journal of Machine Tools and Manufacture, Vol. 48, No. 24, 2008, pp. 1637-1645, 10.1016/j.ijmachtools.2008.07.006.

[2] Budak, E., An Analytical Design Method for Milling Cutters with Non Constant Pitch to Increase Stability, Part 1, Journal of Manufacturing Science and Engineering, Vol. 125, No. 1, 2003, pp. 29-34, 10.1115/1.1536655.

[3] Budak, E., An Analytical Design Method for Milling Cutters with Non constant Pitch to Increase Stability, Part 2, Journal of Manufacturing Science and Engineering, Vol. 125, No. 1, 2003, pp. 35-38, 10.1115/1.1536656.

[4] Sims, N. D., Fast Chatter Stability Prediction for Variable Helix Milling Tools, Proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science, Vol. 230, No. 1, 2016, pp. 133-144, 10.1177/0954406215585367.

[5] Wang, Y., Wang, T., and Yu, Z., et al, Chatter Prediction for Variable Pitch and Variable Helix Milling, Shock and Vibration, Vol. 2015, pp. 1-9, 10.1155/2015/419172.

[6] Otto, A., Rauh, S., and Ihlenfeldt, S., et al, Stability of Milling with Non-Uniform Pitch and Variable Helix Tools, Int J Adv Manuf Technol, Vol. 89, 2017, pp. 2613-2625, 10.1007/s00170-016-9762-2.

[7] Suzuki, N., Kojima, T., and Hino, R., et al, A Novel Design Method of Irregular Pitch Cutters to Attain Simultaneous Suppression of Multi-Mode Regenerations, Procedia CIRP, Vol. 4, 2012, pp. 98-102, 10.1016/j.procir.2012.10.018.

[8] Zatarain, M., Dombovari, Z., Stability Analysis of Milling with Irregular Pitch Tools by The Implicit Subspace Iteration Method, Int. J. Dynam. Control, Vol. 2, No. 1, 2014, pp. 26-34, 10.1007/s40435-013-0052-7.

[9] Iglesias, A., Dombovari, Z., and Gonzalez, G., et al, Optimum Selection of Variable Pitch for Chatter Suppression in Face Milling Operations, Materials, Vol. 12, No. 112, 2018, pp. 1-22, 10.3390/ma12010112.

[10] Altintaş, Y., Budak, E., Analytical Prediction of Stability Lobes in Milling, CIRP Annals, Vol. 44, No. 1, 1995, pp. 357-362, 10.1016/S0007-8506(07)62342-7.

[11] Quintana, G., Ciurana, J., Chatter in Machining Processes, International Journal of Machine Tools and Manufacture, Vol. 51, No. 5, 2011, pp. 363-376, 10.1016/j.ijmachtools.2011.01.001.