Enhancing Milling Surface Finish: The Role of Servo Parameters and Machining Stability

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Received: 14 June 2024 | Revised: 11 July 2024 | Accepted: 13 July 2024

ABSTRACT

Abnormal machining vibrations and inconsistent machining quality are commonly observed in high-speed machining operations and are often attributed to the inappropriate characteristics of servo dynamics and structural resonance caused by feeding motions with higher jerk. An understanding of the manner in which distinct servo system parameters impact machining, can facilitate the refinement of machine tool tuning, thereby enabling the achievement of desired machining outcomes. In practical terms, the servo parameters, including feeding acceleration and jerk, control gains, and feed-forward compensation, can be appropriately determined based on the characteristics of the machine in question, such as the presence of dynamic errors in positioning and contouring paths. This study aims to evaluate the interactive effects between servo parameters and machining parameters to gain insight into their influence on machining quality. In order to achieve this objective, different servo parameters were tuned to meet various machining requirements, and cutting experiments were conducted with consideration of the cutter stability. The results are expected to provide guidance on the control of servo systems and the optimization of machining parameters, ensuring that servo tuning effectively enhances machine tool cutting performance.

Keywords-cutting conditions; machining stability; servo parameters; surface quality

I. INTRODUCTION

High-performance machining is substantial for industries that require high precision, efficiency, and the capacity to work with advanced materials and complex part designs. A high surface finish in machined parts is vital for ensuring durability against wear and fatigue under loading, as well as for their precise assembly with other components [1]. However, the surface quality and dimensional accuracy of machined parts are influenced by various factors, including machining conditions, tool geometry and vibrations, cutting parameters, and machining dynamics [2-4]. In particular, surface finish can be deteriorated due to machining vibrations caused by improper machining conditions and process parameters [5-8].

In addition to structural characteristics, the feeding mechanism and servo parameters associated with the control system have exerted a considerable influence on the precision and stability of the cutting process, which in turn have direct impact on the geometric accuracy and surface quality of the workpiece [9-11]. The contouring performance of a machining operation may be adversely affected by structural vibration resulting from high acceleration motion in the feeding mechanism. As shown by authors in [12], the table feed speed has the potential to impact the dynamic behavior of the worktable, which is regarded as a pivotal factor influencing the quality of the machining process. The impact of feed drive system motion errors on machined surface texture was evaluated through simulation and experimentation [11, 13], respectively. Moreover, authors in [14] demonstrated that the vibration of the machine tool structure can be influenced by the servo conditions of the feed drive systems, which accordingly affects motion tracking errors. Furthermore, in [15], it was verified that the dynamic compliance of a milling tool can be enhanced by the appropriate alteration of feed drive control parameters, improving the machining capability. Authors in [16] additionally proposed a novel feed drive controller tuning strategy to enhance machining stability considering the servo feedback response and predicted tool tip compliance. These studies highlight the importance of servo parameters. As documented in [17], proper servo parameter tuning, taking into account the mechanical and servo characteristics of the feed system, can effectively reduce contouring errors in the synchronous drive of multi-axis machining.

The servo control system of a Computerized Numerical Control (CNC) machine tool is constituted of a motion controller, a servo system, and a feeding mechanism with a servo motor [18, 19]. The motion controller is tasked with the conversion of the machining program into a position command, which is then used to regulate the motion through the feeding mechanism and servo system. This ultimately determines the positioning accuracy and, subsequently, the precision of the CNC machine tool. Servo systems are frequently designed with a multi-loop architecture, comprising the servo motor current loop, the velocity and position loop of the feed system, and feed-forward compensation to enhance steady-state and transient control performance [20]. Servo parameters include, motion velocity, acceleration and deceleration, jerk in the feeding path, and others, such as loop gain and feed-forward compensation. In particular, the interaction between the mechanical system and the servo system becomes more intricate when the machine tool operates at high speeds and accelerations, which in turn affects system performance. Authors in [21] confirmed that the appropriate adjustment of acceleration and deceleration in response to changing load conditions can effectively improve processing efficiency. The discrepancies in these parameters may impact the precision of the workpiece, the surface finish, the processing time, and other factors. Authors in [13] exhibited that the occurrence of blemishes on the surface resulting from ball-end milling, can be mitigated by minimizing the rapid change in velocity along the C-axis and by enhancing the acceleration and deceleration processes. Consequently, it is essential to adjust the servo system parameters in accordance with the specific machining requirements to optimize the overall performance. In order to achieve this objective, controllers have been developed with servo tuning functions [22-24], which are capable of modeling the servo characteristics of the feeding mechanism system and automatically adjusting the controller parameters based on the selected machining mode, with the aim of achieving a high surface finish, high accuracy, or high efficiency.

The servo parameter tuning methodology was established with the objective of reducing dynamic contouring errors, defined as the deviation between the path of the NC code and the actual contouring path [25-27]. In [25] a practical servo tuning method for high-speed machine tools aiming to optimize contouring accuracies was presented. The tuning process is based on iterative measurement and dynamic simulation models, which are used to derive appropriate parameters, such as acceleration time and position loop gain. Authors in [26] put forth an intelligent servo tuning method for position and velocity loop parameters, employing iterative circular tests based on linear scale signals. In a further development of practice, authors in [27] proposed a servo tuning methodology to adjust servo parameters based on requirements for machining performance, which they defined as high precision, high speed, and high quality. The influence of servo parameters, including jerk, acceleration limits, and corner velocity, on dynamic errors across diverse machining modes was examined, providing a foundation for tuning criteria. As documented, discrepancies in the electromechanical attributes of the feeding apparatus can precipitate a range of complications, including machine vibrations, suboptimal surface texture, and inaccuracy in workpiece dimensions. The machining performance of the milling system can be enhanced by improving the dynamic characteristics of the servo drive system, specifically by optimizing the servo parameters. This has prompted researchers to focus their efforts on developing a method for adjusting the servo parameters in order to reduce the positioning precision and contouring accuracy of the feeding system in tooling. Conversely, the machining performance of the milling process can be enhanced by selecting appropriate cutting conditions, based on the machining stability lobes of the cutter, which are determined by the interaction of the dynamics of the spindle tool and cutting behavior with the workpiece. Thus, machining stability was regarded as an indicator to quantify the impact of the tool's dynamic characteristics on the machining performance under defined cutting conditions, free from chatter. This approach could potentially enhance the surface quality of the workpiece. An understanding of the influence of different servo system parameters on machining can facilitate the refinement of machine tool tuning to achieve the desired machining outcomes. The objective of this study is to investigate the interactive effects of servo and machining parameters on machining performance. The findings can provide valuable insights for optimizing servo control and parameters, ensuring that servo tuning effectively enhances the cutting performance of machine tools.

II. METHODS AND EXPERIMENTAL ORGANIZATION

The primary stages of this study's methodology include: the configuration of servo parameters for the feeding system of a milling machine, the assessment of the milling cutter's machining stability, and the performance of milling experiments and surface roughness measurement.

A. Servo Parameters

Basically, the servo parameters related to the feed motion are the most important, including the adjustment of the acceleration and deceleration of the feed motion, and the acceleration time of the servo system. The acceleration of the feeding motion has a significant impact on the surface quality, geometric accuracy, and efficiency of the machining process. The majority of controllers provide the functionality of a servo tuning system, which is used to ascertain the optimal parameters for the following processing requirements:

- High surface quality mode: use as little acceleration/deceleration as possible during machining to reduce jerk and oscillation in the feed motion to achieve high surface quality.
- High accuracy mode: the path error must be small, and the corresponding corner error and curve geometry error can be reduced to achieve high accuracy of the part geometry.
- High processing efficiency mode: increase the acceleration deceleration and the shorter the acceleration time to reduce the processing time.

In this study, the automatic servo parameters tuning system developed by the Industrial Technology Research Institute in Taiwan (ITRI, Taiwan) [28] was employed to ascertain the optimal servo parameters for meeting the specified processing requirements. During the optimization process, the system dynamic errors, including axial position tracking error, corner contour tracking error, and geometric error, were identified and minimized by adjusting the acceleration parameters for the feeding motion under different cutting paths. The machining tests used to optimize the servo parameters were carried out on a vertical milling machine (QUSA, MV154) with a controller (Fanuc, 0iMD). In addition to the default settings provided by the manufacturer, two servo parameter modes with distinct requirements were appropriately calibrated: the high surface quality priority mode (HQ mode) and the high geometry accuracy mode. Based on [28], three sets of servo parameters were identified and listed in Table I.

TABLE I. SERVO PARAMETERS FOR DIFFERENT MACHINING REQUIREMENT

Servo mode	Parameter no	Unit	X	Y	Z	Machining time
First mode: Factory default setting	P1735 1737	mm/s^2	400	400	400	49 min 39 s
	P1660	mm/s^2	800	800	800	
	P1783	mm/ min	266	266	266	
	P1769	msec	37	37	37	
Second mode: Accuracy priority	P1735 1737	mm/s^2	581	547	722	49 min 31 s
	P1660	mm/s^2	623	600	821	
	P1783	mm/min	133	133	133	
	P1769	msec	21	21	21	
Third mode: Surface finish priority	P1735 1737	mm/s^2	355	347	441	50 min 09 s
	P1660	mm/s^2	393	374	474	
	P1783	mm/min	133	133	133	
	P1769	msec	50	50	50	

As described in [24], the maximum allowable acceleration rate for the deceleration function, based on acceleration in circular interpolation for each axis, is represented by parameter 1735. Parameter 1737 represents the maximum allowable acceleration rate for the deceleration function based on acceleration in AI contour control for each axis. The maximum allowable acceleration rate in acceleration/deceleration before interpolation for each axis is indicated by parameter 1660. Parameter 1769 denotes the time constant for acceleration/deceleration following the cessation of feed interpolation in the acceleration/deceleration before interpolation mode. The maximum allowable feed rate difference for feed rate determination based on corner feed rate difference is defined by parameter 1783. The potential for subsequent machining errors at a corner can be mitigated. The servo parameters for feeding motion were implemented in the controller for a series of machining tests. As evidenced in Table I, the third servo mode for high-quality performance exhibits a reduced limitation of acceleration in corner feeding compared to other modes, yet there is no notable increase in machining time.

B. *Evaluation of Machining Stability of Milling Tool*

In order to evaluate the optimum machining conditions, specifically the cutting depth and spindle speed in a stable region without inducing chatter, the identification of parameters that could potentially enhance the material removal rate while simultaneously improving surface quality were allowed [29]. The machining stability of the cutter is primarily contingent upon the frequency response function, as measured at the tool end, and the cutting resistance of the cutter in relation to the workpiece. This can be predicted by an analytical model developed in [30], as expressed in (1), which delineates the relationship between chatter-free axial cutting depths (Z_{min}) and the spindle speed (n) in end-mill operation:

$$Z_{min} = \frac{-1}{NK_t K_r R_e(\omega)} \quad (1)$$

$$n = \frac{60\omega_c}{N(2k\pi+\phi)}, \phi = 3\pi - 2\tan^{-1}(I_m/R_e),$$

$$k = lobes(0,1,2\ldots) \quad (2)$$

where K_t and K_r are cutting resistance coefficients in the tangential and radial directions to the cutter, N is the number of cutter teeth, k is the lobe number and $R_e(\omega)$ is the real part of the frequency response function of the spindle tool tip.

In this study, a ball cutter with two flutes, a diameter of 10 mm, and a radius of 5 mm was employed for finishing machining against the workpiece material, which was an aluminum alloy (AL 6061). The frequency response of the cutter was obtained through the implementation of a tapping test on the milling spindle, as observed in Figure 1(a), while the frequency response function measured at the tool tip is shown in Figure 1(b), which indicates that the maximum amplitude of the tool is 1.64 µm/N, occurring at a resonance frequency of 3,758 Hz. This mode, which exhibited a notable amplitude, was employed to assess the stability lobes of the cutter. In order to calculate the stability of the machining process, the cutting resistance coefficients of the carbide cutter were found to be Kt = 796 N/mm² and Kr = 0.21 [30]. Figure 1(c) presents the stability lobes of the cutter. The critical cutting depth for the tool is approximately 2.0 mm, irrespective of the machining speed, so as to prevent chatter. It is noteworthy that at a spindle speed of approximately 5,200 rpm, the lobes boundary suggests that the cutting depth for stable machining may reach 4.0 mm. It can be expected that stable machining with a higher material removal rate and superior surface quality can be achieved under these cutting conditions.

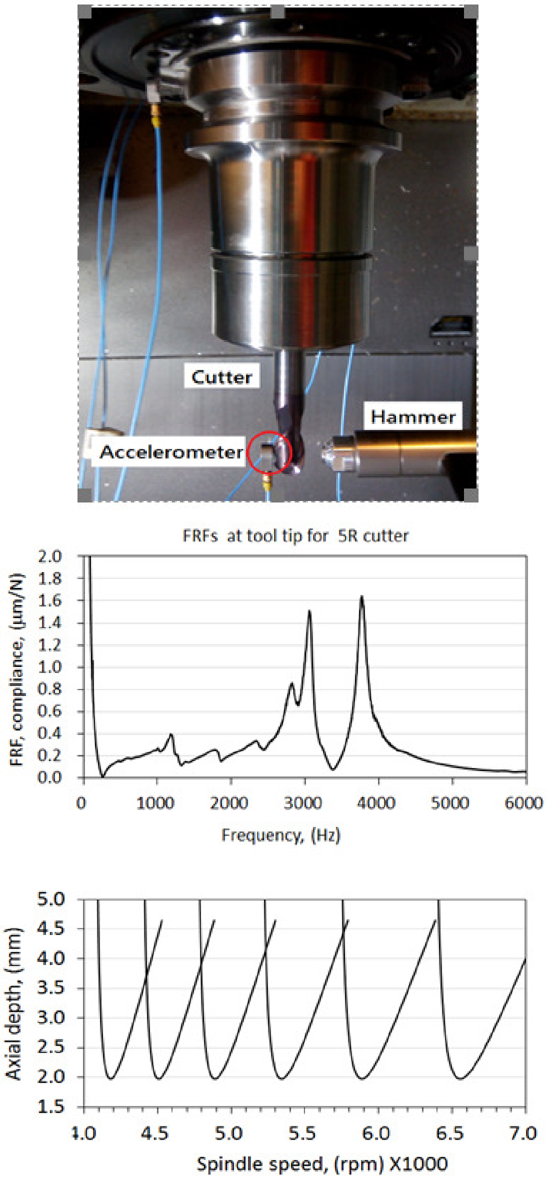

Fig. 1. (a) Tapping test conducted on milling cutter, (b) frequency response function at tool tip, and (c) machining stability lobes diagram of cutter.

C. Machining Tests

In this experiment, cutting tests on curved surface profiles were performed using a vertical milling machine with different servo parameters. The workpiece displays a waveform profile at varying depths. The detailed geometry dimensions are portrayed in Figure 2. The primary cutting plane was the *XZ* plane, as presented in Figure 3(a). The stability of mechanical performance and the influence of servo parameter adjustments were verified by conducting cutting tests with varying depths. In particular, within the motion path, there are inflection points on the surface concave surface profile with a significant change in feeding acceleration, which is expected to induce severe cutting vibrations of the spindle tool and workpiece in feeding, affecting machining quality.

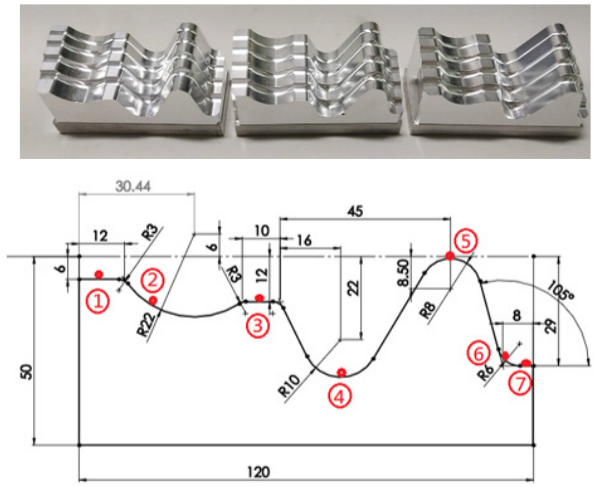

Fig. 2. (a) Machined workpieces and (b) Geometry dimension of the surface profile of the worjpiece.

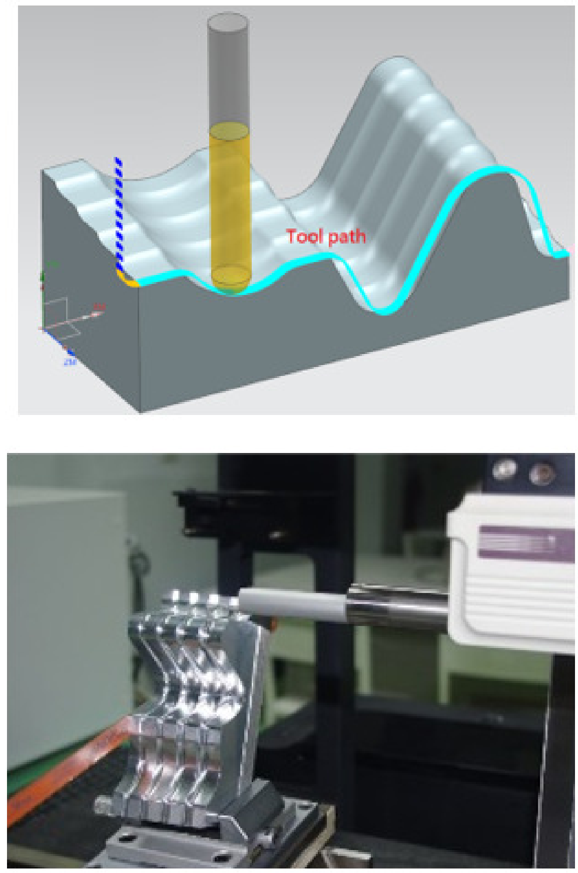

Fig. 3. (a) Schematic of the machining path along the profile, (b) measuremens of surface roughness.

Prior to the contour finishing process, the specimens were initially milled from the original stock material in order to create the desired curved surface through the implementation of rough machining techniques. Three specimens were prepared for the finishing machining operation. Each specimen was machined in accordance with the five surface profiles at varying depths, specifically 0.3 mm, 1.0 mm, 2.0 mm, 3.0 mm, and 4.0 mm, under the guidance of designated servo parameters. The cutting conditions were established at a spindle speed of 5,220 rpm, a feed rate of 1,090 mm/min, and a radial pitch of 0.2 mm. Subsequently, the surface roughness was evaluated through the utilization of a Mitutoyo Surftest SV-3000, exhibiting a resolution of 0.001 µm, as illustrated in Figure 3(b). The measured positions are displayed in Figure 2(b), with seven data points for each wave surface. The morphologies of the machined surface were analyzed using a white light interferometer (Zygo, NewView™ 8000 Series), and the results are illustrated in Figure 4. The figure depicts the surface textures in the flat, convex, and concave areas, respectively.

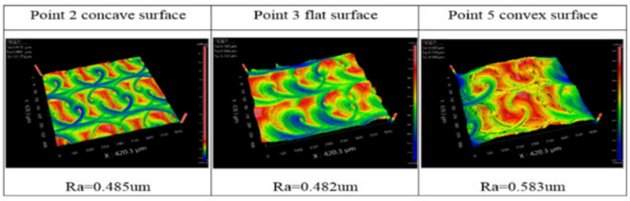

Fig. 4. Typical morphologies of the machined surfaces generated under defalt servo mode.

III. RESULTS AND DISCUSSION

A. First Set of Servo Parameters(default)

Figure 5 demonstrates the variations in roughness along the curved profile generated under machining with different cutting depths, using the default servo parameters. The surface roughness (*Ra*) was found between 0.3 µm and 1.2 µm. For specific cutting depths, the surface roughness exhibited variability along the surface profile.

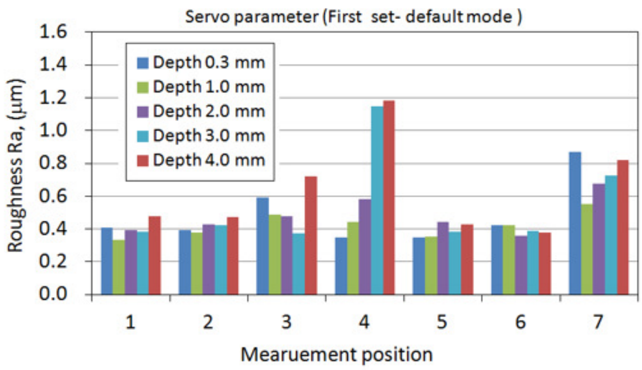

Fig. 5. Variations of the roughness along surface profle with different cutting depth under default servo mode.

The highest roughness values were observed at points 3, 4, and 7. Points 3 and 4 are situated on a flat surface, where the influence of friction from the cutter is evident due to the reduced cutting speed. The highest roughness was observed at the concave surface, point 4, where the cutter encounters a change in feeding acceleration resulting from the transition in the cutting path along the surface profile. This may induce apparent vibration, which could potentially impact the surface morphology. However, further verification through additional machining is necessary in future studies to monitor the variation of spindle tool vibration. Furthermore, the mean values of surface roughness along each curve profile with specific cutting depths are presented for comparison in Figure 6. It was observed that an increase in cutting depth resulted in a corresponding increase in surface roughness. When the depth cut was less than 2 mm, the surface roughness exhibited a range of 0.425 µm to 0.484 µm. At cutting depths of 3 mm and 4 mm, the mean surface roughness increased to 0.546 µm and 0.64 µm, respectively. As displayed in the stability lobes diagram, the critical cutting depth of the cutter is approximately 2.0 mm, with cutting depths below this value falling within the stable zone. Machining above 2 mm may result in unstable operations, potentially impacting the surface morphology. However, the stability lobes indicate that at a speed of approximately 5,200 rpm, the maximum stable cutting depth is 4.0 mm, which is situated at the boundary of the stability lobe. It is possible to utilize this higher cutting depth in machining without chatter at this spindle speed. The overall average roughness is 0.51 µm for machining under the default servo parameters set on the CNC controller.

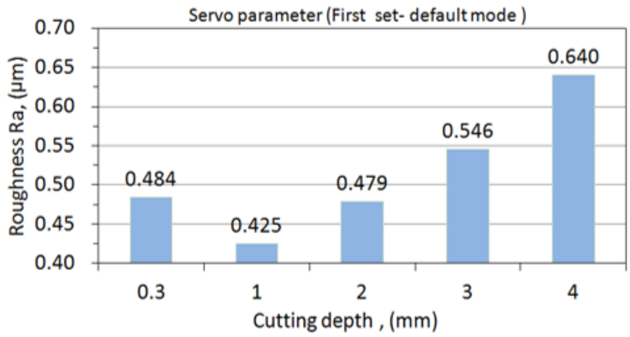

Fig. 6. Comparison of the mean value of roughness at different surface profiles.

B. Second Set of Servo Parameters

The second servo mode was designed with the objective of achieving high-accuracy machining. Figure 7 portrays the variations in surface roughness along a curved surface with different cutting depths under this servo mode. The data demonstrate a roughness scattering between 0.3 µm and 1.6 µm for cutting depths from 0.3 mm to 4 mm. It is noteworthy that the roughness measured at point 4 is markedly higher than at other points for machining with varying depths. The mean values of roughness generated with different cutting depths are presented in Figure 8. It is observed that the roughness at the concave area, point 4, is significantly higher than at other points. In general, roughness generated by this servo mode is comparable to that generated by the first servo mode with the default settings.

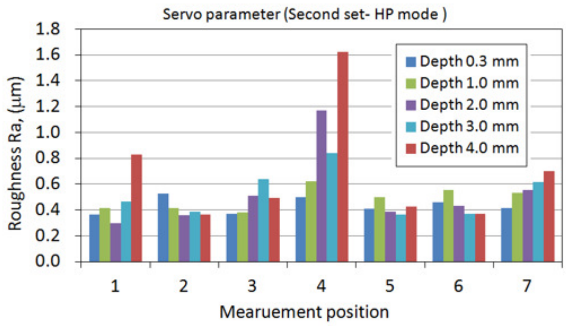

Fig. 7. Variations of the roughness along surface profle with different cutting depth under second servo mode.

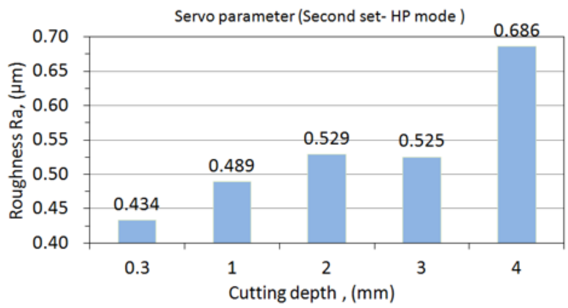

Fig. 8. Comparison of the mean value of roughness at different surface profiles.

C. *Third Group of Servo Parameters*

Figure 9 illustrates the fluctuations in surface roughness along the curved surface when machining with the third servo parameter is configured. In this case, the roughness falls within the range from 0.3 µm to 0.8 µm for varying cutting depths. Figure 10 shows the mean values of surface roughness at each curve profile under different cutting depths. The mean roughness demonstrates a consistent variation, ranging from 0.437 µm to 0.478 µm, for surface profiles with varying cutting depths, from 0.3 mm to 4 mm. It was determined that the surface finish was enhanced when the machining was conducted under this set of servo parameters, which were calibrated to achieve optimal surface quality. When the cutting depth exceeds 3 mm and 4 mm, the surface roughness can be maintained at a lower value. Specifically, the roughness at point 4 was reduced to approximately 0.7 µm to 0.8 µm. The overall mean roughness is 0.437 µm for machining under the third servo mode, which was selected to achieve a high surface finish.

D. *Comparison of the Effectvines of Servo Modes*

In order to evaluate the impact of servo parameters on the quality of the machined surface, the mean surface finish values at varying cutting depths are presented in Figure 11. It is evident that the surface finish under the first and second servo modes is markedly inferior to that under the third mode. The initial two modes exhibit elevated acceleration and deceleration during the feeding motion, which gives rise to jerk and pronounced vibrations. These factors collectively impair surface texture and finish. Furthermore, the second mode permits a higher acceleration than the one allowed by the default mode, which results in a greater degree of roughness in comparison to the first mode. In contrast, the third mode, which exhibits lower acceleration during the feeding motion, results in superior surface quality with a mean roughness of approximately 0.468 µm. It can be seen that the third mode maintains stable machining quality up to a cutting depth of 4 mm, which is located at the boundary of the stability lobe. Furthermore, it ensures better surface roughness than the default parameters. These results indicate that tuning servo parameters, particularly acceleration and deceleration, can significantly improve surface quality. Additionally, higher cutting depths can be used to enhance both material removal rate and surface quality, considering the stability of the cutter.

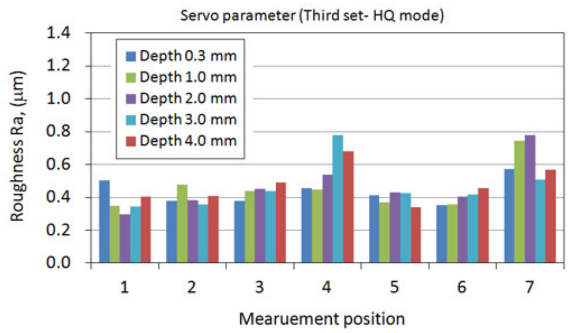

Fig. 9. Variations of the roughness along surface profle with different cutting depth under third servo mode.

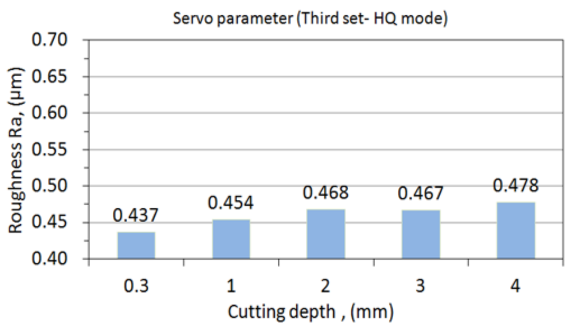

Fig. 10. Comparison of the mean value of roughness at different surface profiles.

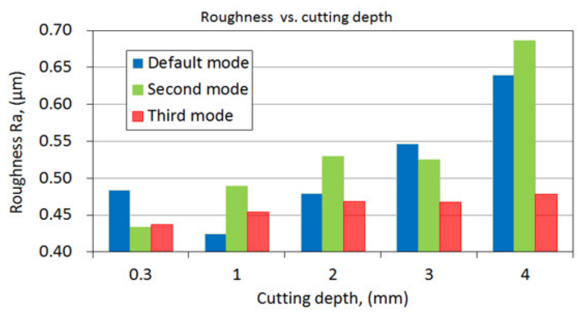

Fig. 11. Comparison of the surface roughness generated under different servo modes.

E. Discussion

The objective of the research was to investigate the impact of servo parameters on milling surface finish, with a particular focus on three distinct sets of servo parameters. The findings provide crucial insights into the optimization of surface quality through precise servo parameter tuning. This includes an investigation of the effects of machining stability and cutting depth. It is of great importance to operate within the stable zone delineated by the stability lobes diagram. Once the critical cutting depth has been exceeded, the quality of the surface begins to deteriorate due to the onset of unstable machining conditions. Moreover, an increase in cutting depth generally corresponds with an increase in surface roughness. Nevertheless, this phenomenon can be counteracted by modifying the servo parameters. To illustrate, the third set of servo parameters, optimized for high surface quality, markedly enhanced the surface finish even at elevated cutting depths in comparison to the default and high-accuracy modes. In particular, the mean surface roughness was maintained at lower values, thereby demonstrating the efficacy of lower acceleration settings in attaining superior surface quality. The impact of acceleration and deceleration on motion, was found to induce vibrations, which resulted in a deterioration of surface quality. The initial and secondary servo modes, which exhibited elevated acceleration and deceleration settings, were observed to result in elevated roughness levels. In contrast, the third servo mode, which featured reduced acceleration, yielded smoother finishes, underscoring the pivotal role of these parameters in surface finish optimization. Integration of servo parameters and stability was made in order to enhance the quality of the machined surface. This approach allowed a more comprehensive understanding of the factors affecting the quality of the milled surface. The optimized third set of servo parameters not only resulted in an improved surface finish, but also permitted higher cutting depths without any quality loss, thereby enhancing productivity and efficiency in milling operations.

In contrast to numerous studies that concentrate exclusively on cutting parameters or machining dynamics, this research integrates servo parameters into the analysis, thereby attempting to present a more comprehensive perspective on the elements influencing surface finish during milling. Prior studies have likewise documented the impact of machining parameters on surface quality. For example, research on end milling processes has highlighted the significance of cutting parameters and machining vibrations [4-8, 29]. These studies demonstrated that cutting parameters within stable or unstable regions of machining stability significantly influence surface roughness. However, the vibration induced was not linked to CNC controller servo settings. Other studies [11-14], have corroborated that elevated acceleration in servo settings can impair surface roughness. However, these studies lacked a quantitative analysis of the relationship between servo parameter adjustments and roughness under varying cutting conditions, which would have enabled direct comparison with the current study. In conclusion, the findings presented in those studies, when considered alongside those of the current research, contribute to the creation of a comprehensive body of knowledge that can inform the development of more efficient manufacturing operations. The findings demonstrate a notable interaction between spindle speed, cutting depth, and servo parameters with respect to surface roughness. This knowledge allows the optimization of machining conditions, resulting in improved surface finishes and enhanced product quality and manufacturing efficiency.

IV. CONCLUSION

The objective of this study was to investigate the impact of optimizing machine tool servo parameters on the surface finish of milling operations. The findings, demonstrated that the optimization of servo settings for enhanced surface quality, as evidenced by a reduction in feeding motion acceleration, led to a notable decrease in surface roughness when compared to the factory default and high-accuracy modes. This underscores the pivotal influence of acceleration and deceleration on surface roughness. Furthermore, the implementation of optimized high-quality servo parameters enabled the attainment of a stable cutting depth of up to 4 mm while maintaining superior surface quality. This configuration also ensured a high-quality surface finish and optimal material removal rates, outperforming other servo modes. In conclusion, the study presents a comprehensive approach that integrates servo parameter adjustments with considerations of machining stability. By precisely adjusting the servo parameters, it is possible to attain the optimal surface quality of the workpiece, consequently enhancing both productivity and efficiency in milling operations.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support for this work provided by the Intelligent Machinery Technology Center, Industrial Technology Research Institute, Taiwan.

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