# STRUCTURAL ANALYSIS OF A MINI THREE-AXIS CNC MICRO-MILLING MACHINE WITH HORIZONTAL SPINDLE CONFIGURATION

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**ABSTRACT:** Micro-milling is an attractive manufacturing process due to its capability to fabricate miniaturized products. In recent years, more compact and affordable computer numerical control (CNC) machines are available on the market. However, there are not many small-sized high-precision milling machines, especially to fabricate micro sized products. In addition, most of the CNC micro-milling machines used vertical spindle frame position and yet there are not many studies available on the application of horizontal spindle frame position especially in terms of structural analysis. Therefore, this paper contributes to the study of the development of a mini three-axis CNC micro-milling machine using horizontal spindle frame position. This paper discusses the horizontal spindle frame design decision, the structural analysis using finite element analysis (FEA), the prototype, and the machining experiment. The study was conducted in the following steps: (1) defining the spindle position configuration, (2) designing the frame structure, (3) performing finite element analysis, (4) building the machine, and (5) performing experiments. The FEA results show the structure critical location is at the top of vertical work-piece table and the lowest natural frequency occurred at 295 Hz. The micro-milling experiments were able to produce fine circular shape and rectangle features with good visible surface quality. The smallest feature of around 200 μm can be produced by the machine.

**KEYWORDS**: *Micro-milling; Horizontal spindle; Structural analysis, Finite element analysis*

## 1.0 INTRODUCTION

The demand for miniaturized products in the micro-size scale is increasing due to the wide range of applications of such products. These products are widely used in many industries including medical-care, biochemical, environment, aerospace, electrical, and other field used micro- and/ or meso-sized components [1]. Theoretically, the micro size features are within the range of 100 μm-10.000 μm [2]. There are many types of mechanical micro-machining processes to produce micro-sized features such as such as micro-turning, micro-drilling, micro-electro discharge machining (EDM), and micro-milling [3]. Recently, micro-milling has become one of the most promising and widely adapted in broad high-tech industrial sectors as it is capable of producing a high complexity feature in various materials including metals, ceramics, and composites [4]. However, the accessibility of the micro-milling machine is still expensive and large in dimension. Yet many available mini micro-milling machines use closed frame structure where their spindles hang on vertical position which is susceptible to vibration.

There are several considerations to be made when designing a proper micro-milling machine which include the strength or stiffness and the cost effectiveness of the machine. In general, the standard of machine tools is performed by the driver system, sensor, control, approach design, and mechanical structure [5, 6]. Modern driver technology is extended as computer numerical control (CNC) machines which must be synchronized with the desired machine performance and high accuracies [7, 8]. Prior to the building of the machine, the rigidity of the machine structure needs to be studied by comparing the frame configurations (i.e., closed frame or open frame), spindle positioning, spindle specification, and other generated parts during the assembling process. In order to build a good quality CNC micro-milling machines, it is essential to perform a structural analysis of the machines and one of the ways is by employing finite element analysis (FEA) to obtain an optimum configuration prior to fabricate the machine [9, 10]. The CNC micro-milling machines must maintain rigidity, accuracy, and precision of linear and rotational movement.

Due to micro scale production needs, CNC micro-milling can be adapted by down scaling the conventional CNC machine [11]. However, some aspects, mainly the design and configurations in conventional CNC machine, cannot be applied directly because of the different mechanism. One of the primary challenges in building micro-milling machines is to maintain precision and accuracy at the micro-scale. The presence of minor vibrations can significantly impact machining quality. Micro-milling typically involves machining features with dimensions on the order of micrometers, which can magnify the effects of vibration to burr formation. A rigid structural frame is essential for minimizing vibration effects. According to Hung et. al. [12] the critical point of micro-milling machine were located mainly at the top of the frame due to the minimum support and the presence of vibration during the machining process. Hence, mitigating vibration and failure specifically for the structural design as the pre-manufacturing step is crucial. This can be done by utilizing finite element analysis. In addition, the vibration can occur due to the position of spindle.

Many of the CNC micro-milling machines use vertical spindle frame position which due to the weight of the spindle can increase the vibration during operation. In addition, there are not many studies available about the use of horizontal spindle frame position especially in terms of structural analysis. Therefore, it is necessary to study the development of a three-axis CNC micro-milling machine using horizontal spindle frame position. The objective of this study is to design and construct a CNC micro-milling machine which could be applied to fabricate micro-sized products using horizontal spindle position frame. To support the designing process, this paper focuses on the structural approach in which FEA was performed in order to achieve an optimum machine structure configuration. The design and structure were also evaluated to predict undesired vibrations during the operation which could disturb the continuity of micro-milling process [13].

It is expected that the development of this CNC micro-milling machine could contribute to the headways of the micro-sized engineering productions and can be used for educational purposes. The outline of this paper is structured as follows: Section 1 introduces the micro-milling and its current development; Section 2 describes the methodology of the proposed study, which is divided into three subsections, namely, spindle position configuration, structure design and finite element analysis, and micro-milling experiments; Section 3 presents and discusses the experimental results; and Section 4 concludes the research findings.

## 2.0 METHODOLOGY

The construction of a CNC micro-milling machine in the present study involved five steps. The first step was defining spindle position configuration. This step is the crucial step in developing a CNC machine. There are not many studies reported about the selection of spindle position configurations. This step is defined mainly based on the specification of the spindle to be used. The second step involved designing the machine using Computer Aided Design (CAD) to perform FEA using Computer Aided Engineering (CAE) of the proposed machine structure. This was followed by the third step which determined the controlling and electrical system, and the fourth step which involved building the machine. Finally, the last step involved testing the machine's performance. However, this paper only focuses on the steps related with structural analysis of the development of CNC micro-milling machine and the performance test results (i.e., Step 1, Step 2, and Step 5).

### 2.1 Step 1: Spindle Position Configuration

The development of the CNC micro-milling machine was started from the study of the frame design. Open and close structures, spindel position, axis placement and configuration were compared based on the criteria from essential parameters including error propogation, stiffness and frame durability [14]. In constructing the CNC micro-milling machine, the motor spindle is considered as the primary part in charge of holding and rotating the milling tool until the tool produces a rotation or cutting motion [15]. Accordingly, all components must comply with the spindle motor specifications in order to build a rigid CNC micro-milling machine frame. In this study, a motor with the specification of 1.5 kW 220V CNC air-cooled spindle motor E20 was used. Moreover, frame structure such as closed or open frame structure must be defined and linear modules were applied to the CNC micro-milling design which included a set of ball screw, linear guides, gantry/table, motor bracket, and motor.

### 2.2 Step 2: Structure Design and Finite Element Analysis

This step was conducted to examine the strength and the capability of the proposed structural design to resist undesired vibrations. The three-dimension structure was designed and assembled using SolidWorks 2021 and the FEA was conducted using ANSYS Workbench version 19.2. The 3D CAD was constructed using two materials: aluminum and steel. Three analyses were performed, namely, static structural, modal analysis and harmonic response analysis. The analysis results depend on the meshing quality and the connection in every face-to-face contact region. The static structural analysis was performed to estimate any undesired deformation and the stress distribution especially equivalent (von-Mises) occurred in static conditions with applied assumptions. In the static structural analysis, the load applied was a "standard earth gravity" towards all bodies and fixed boundary condition was at the bottom of the machine body. All assigned parts were connected using a particular connection and contact region. Afterwards, the modal analysis was conducted followed by harmonic response analysis to obtain a thorough analysis to find the frequency response of the system. Modal analysis is important in order to identify its own characteristic movement or vibration pattern associated with the corresponding natural frequency. In addition, a subsequent harmonic analysis stage was performed in order to find the dominant frequency on response function graphs. In these analyses, the cutting force in the tool located in the spindle is acted as the load.

## 2.3 Step 5: Micro-milling Experiment

Once the machine was built, micro-milling experiments were conducted to validate and examine the performance of the built machine. Circular and rectangle features were produced using slot milling process on acrylic workpiece. The experiments were conducted mainly to observe the surface quality and the movements of the axes. Two circular patterns having an "O" shape with external diameter of 2.2 mm and internal diameter of 0.2 mm and external diameter of 2.5 mm and internal diameter of 0.5 mm were produced. In addition, a rectangle shape with external size of 5 mm x 2.2 mm and internal shape of 3 mm x 0.2 mm were produced (Figure 1). The results were measured using a microscope with a resolution of 5 MP and 10 x magnification. In addition, surface quality such as burr formation was also observed.

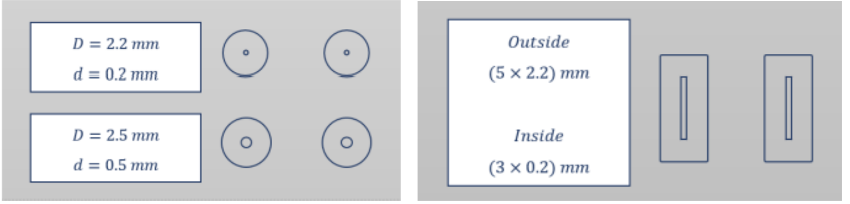



Figure 1: Features selected for micro-milling experiments consist of circular features (left) and rectangle features (right)

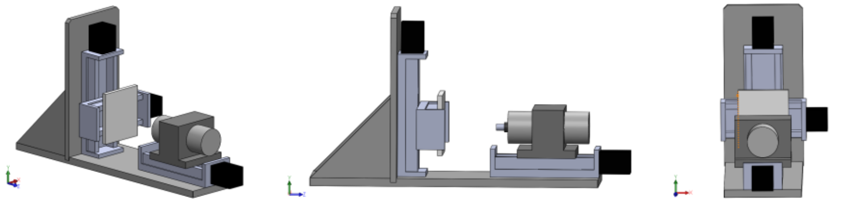
## 3.0 RESULTS AND DISCUSSION

This section presents and discusses the proposed design, the finite element structural analysis and the micro-milling experiment results.

### 3.1 Proposed Micro-milling Machine Structure Design

From the literature studies and in order to have a compact size (mini) milling CNC machine, an open frame structure design was selected. The heavy spindle attached to the linear module was placed on the horizontal z-axis position to minimize the load and vibration transmitted to the frame. Hence, the workpiece table attached to the two stacked linear modules (x and y axes) was positioned vertically as shown in Figure 2. The minimalist concept of the frame was that the main structure has only 4 parts: a horizontal base, a vertical base, and two triangular supports securing the vertical base to the horizontal base.

The travel lengths of the axes are 100 mm, 120 mm and 160 mm for x-axis, y-axis and z-axis, respectively. In order to optimize the performance of the chosen configuration and the manufacturing cost, the combination of aluminum and structural steel materials is employed. Aluminum with lighter and softer characteristics is commonly used as supporting components for linear axis modules, holder, gantry table, and others due to its better machinability [16]. Due to its higher rigidity and stiffness, steel was chosen for the frame structure. The proposed design was simplified into geometrical shapes without affecting the critical components for finite element analysis as shown in Figure 2.



(a) (b) (c)

Figure 2: 3D design after shape simplification (a) isometric view, (b) side view, and (c) front view

### 3.2 Finite Element Analysis (FEA)

Static structural, modal, and harmonic response analyses were performed using ANSYS Workbench version 19.2. The fine meshing was used with body sizing of 20 mm and method of "hex dominant". Figure 3 shows the final meshing illustration.

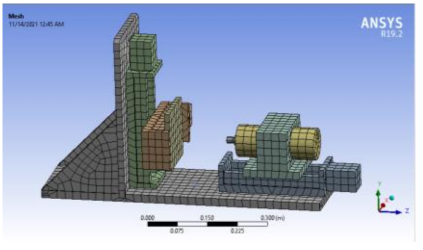



Figure 3: Final meshing generated on the machine structure

**Structural Analysis Result**. The vertical base of the frame structure is susceptible to deformation under static load and cutting forces during the machining. Under static load, the vertical base tends to bend forward due to the significant weight of the two linear x- and y-axis modules and the workpiece table, as shown in Figure 4. Figure 5 (a) shows the maximum deformation of 1.102 μm (marked with red color) experienced by the top part of the vertical base. During the machining, the cutting forces opposes the static load reducing the forward bend of the vertical base. The two triangular supports hold the vertical base to avoid severe bending as shown in Figure 5 (b). This result confirmed the previous study conducted by Hung et. al. that the deformation of milling machine frame are commonly occurs at the top of the machine due to the presence of the force during the milling process [12].

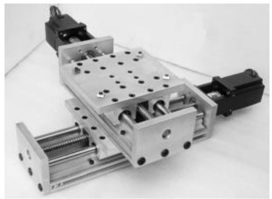
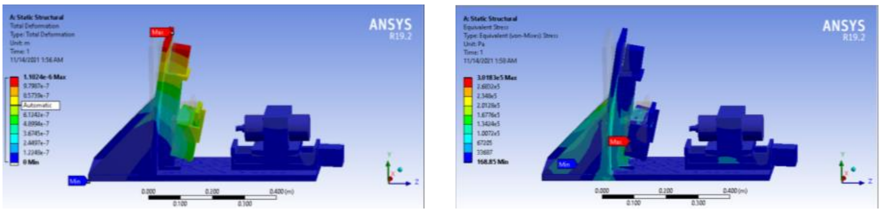


Figure 4: Stacked linear x- and y-axis modules




(a) (b)

Figure 5: Result from the simulation (a) Total deformation, and (b) Equivalent (von-Mises) stress

**Modal Analysis and Harmonic Response Analysis.** In this ANSYS simulation, the cutting force was applied -1.2 N in z-direction (i.e. the force applied to the workpiece table from the cutting tool attached to the spindle) and 0.9 N in y-direction [17]. Figure 6 shows the setup for modal and harmonic response analyses.

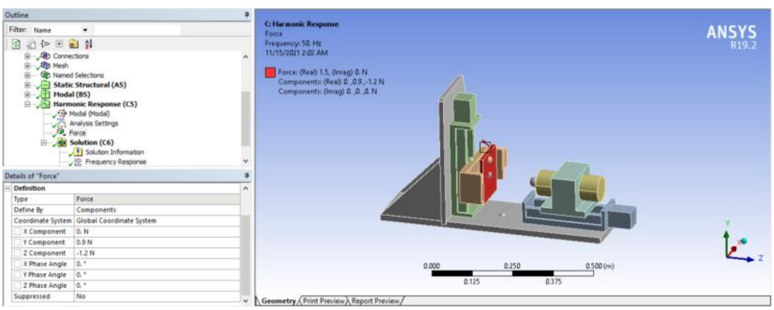



Figure 6: Force applied towards the workpiece table.

Table 1: Frequencies of the mode shapes

| Mode | Frequency (Hz) |
|---|---|
| *1* | 249.62 |
| *2* | 581.54 |
| *3* | 671.03 |
| *4* | 708.99 |
| *5* | 849.09 |
| *6* | 859.58 |
| *7* | 1174.1 |
| *8* | 1201.1 |

The modal analysis results are presented in Table 1. The lowest frequency occurred in mode 1 is 249.62 Hz. In general, a mode shape is excited if there is an external force having the same or similar frequency with the mode shape frequency [18]. Each mode shape has its own characteristic movement or vibration pattern associated with its first natural frequency [19]. During the machining process, the spindle rotates at a particular frequency. When this frequency matches with mode shape frequency, it causes a resonance which leads to undesired vibration and adversely affect the accuracy of the cutting results [20]. The first mode of the natural frequency 249.62 Hz converts to around 15,000 rpm. The spindle used has maximum rotation speed of 5,000 or about 83 Hz. Hence, it is save to be used since its working operation is far below from the first mode vibration.

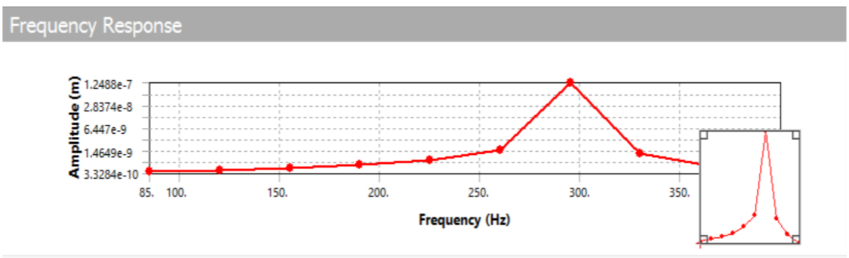
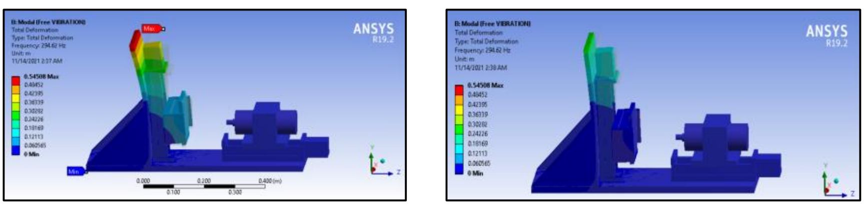
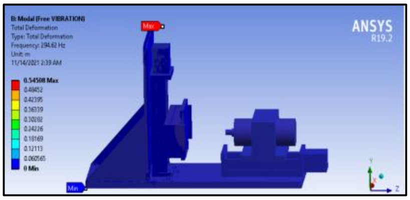



Figure 7: Frequency response of the system

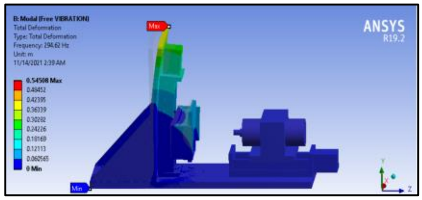
For further analysis, the bode plot is presented in Figure 7. The peak frequency corresponds to the first mode frequency. As can be seen, the curve starts to increase at around 150 Hz. This frequency is still far from the previously mentioned 83 Hz of the maximum spindle vibration.



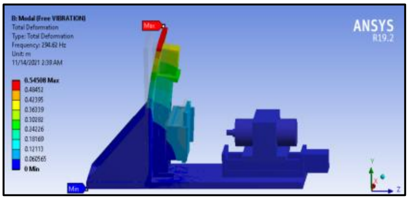

(a) (b)




(c)




(d)



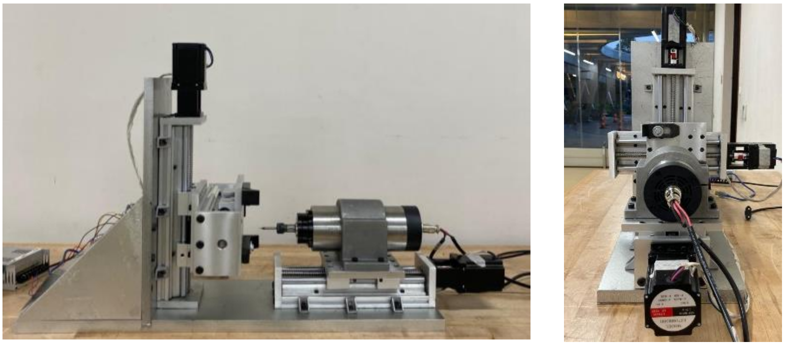

(e)

Figure 8: First mode shape result from modal analysis (a) Phase 1, (b) Phase 2, (c) Phase 3, (d) Phase 4, and (e) Phase 5

If the harmonic response is illustrated in five phases, it reflects the ways of the vibration occurred (see Figure 8 (a-e)). The pictures depicted the sinusoidal movement of the structure which concentrated at the upper part of the workpiece table. At the first phase, the top part of the vertical base experiences a maximum deformation distance in the direction bending away from the spindle. Subsequently, it moves to finally reach the normal static condition at phase 3. Then, at the last phase, the vertical base bends towards the spindle maximumly, opposite to phase 1. Moreover, from the color, it can be seen that the fourth phase exhibit higher deformation compared to the second phase. Apparently, the behavior of the structure was similar to that of the static structural analysis. This gave evidence that the CNC micro-milling machine had the most vulnerable point or experienced the largest deformation point at the top of the vertical frame traced with red marking. This result confirms that the presence of the two triangular supports at the vertical frame minimizes the deflection especially when the machine vibrates during the operation.

Further observation from the Figure 8, looking at the workpiece table, the deformation distance is about one fifth of the maximum deformation distance, which can be calculated to be around 0.22 μm. Besides, this can happen only at the mode 1 frequency which is far below the spindle maximum speed. This confirms that the machining process is still within the limit of micro-milling accuracy.

### 3.3 CNC Micro-milling Machine Prototype



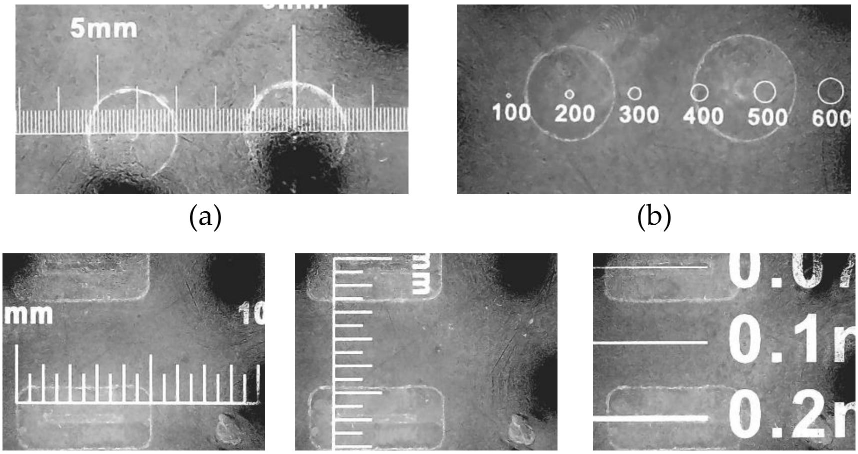
(a) (b)

Figure 9: The built 3-axis CNC micro-milling machine (a) side view, and (b) front view

Once the design was completed and confirmed by FEA, the CNC micro-milling machine was then built. The machine size was estimated to be around 700 mm×200 mm×430 mm. The weight from each axis module was approximately 5 kg. The two triangular supports were firmly bolted to the vertical and horizontal bases forming a rigid structure. The spindle motor was clamped on top of the z-axis module table, as shown in Figure 9.

### 3.4 Micro-milling Experiments

The test was conducted to verify if the built of the CNC micro-milling machine would be able to perform the required function. The circular and rectangular features in Figure 1 were produced using a slot milling process on acrylic workpieces. The experiments were conducted mainly to observe the surface quality and the movements accuracy of the axes. During the operation, the maximum spindle speed was 4,356 rpm or equal to 72.6 Hz. The micro-milling machining outcomes were examined using an optical microscope, as shown in Figures 10 (a)–(e). For the 2 mm diameter circular feature in Figures 10 (a) and (b), the micro-milling machine was able to produce circular features. However, the diameter measurement is larger compared to the desired diameter with approximate tolerance of 10 μm. Figures 10 (c)–(e) illustrate the results for milling rectangular features, which are identical to the intended dimensions: 5 mm in length, 2.2 mm in width, and 0.2 mm (200 μm) in thickness for rectangular inside features. These findings suggest a better capability in creating rectangular features compared to circular ones. Additionally, larger features exhibited enhanced accuracy.




(a) (b)

(c) (d) (e)

Figure 10: Testing result of (a) diameter circularity and dimension, (b) protruded circle, (c) length of rectangular, (d) width of rectangular, and (e) thickness of rectangular inside features.

Besides, the results show an even finish along the features due to the minimum presents of burr which indicate a good machining quality similar to the optimum results achieved by Saptaji et al. [11]. The absence of burrs also indicates that the machine structure is rigid and stable, minimizing vibrations that can lead to reducing the burr formation. This revealed that the machine frame, spindle, and other critical components can adequately withstand machining forces similar to Zhang et al. [21].

## 4.0 CONCLUSION

The goal of this study was to design the structure for a compact size CNC machine that is able to perform micro-milling to fabricate micro-sized products. The focus was to analyze the structure design, prototype, and test the performance of the machine. The analyses confirmed that the machine operation will definitely not cause large vibration since it is far from the machine's natural frequency. The machine was designed with the horizontal spindle position configuration on the stand-alone z-axis module and the workpiece table on vertical position with x- and y-axis modules that are positionally stacked with x-axis is on the top. The overall dimension of the machine is 700 mm × 200 mm × 430 mm in length, width, and height, respectively. The FEA results showed that the maximum deformation distance is located at the top of vertical base of the structure. Meanwhile, the workpiece table located at the middle of the vertical base and may experience only half the maximum deformation distance than that of the top of vertical base. The mode shape 1 occurs at frequency of 249.62 Hz corresponds to around 15,000 rpm spindle speed. However, the maximum operation of the spindle used is 4,356 rpm or equal to 72.6 Hz confirming that the cutting accuracy is not affected by the natural frequency of the machine during the machining process. The mini-CNC micro-milling machine prototype was able to produce fine circular shapes and rectangle features with high dimensional accuracy and good surface quality with the smallest feature produced measuring about 200 μm. The absence of burr formation also revealed that the machine configuration and rigidity were able to adequately withstand machining forces and vibration during the operation.

It is envisaged that future research might consider installing safety systems such as safety guards and emergency stop buttons. In addition, applying materials with better damping capacity in certain supporting parts might also be worthy of consideration.

## AUTHOR CONTRIBUTIONS

K. Saptaji: Conceptualization, methodology, validation, supervision, writing- reviewing and editing; M.A. Octaviani: Methodology, data collection and validation, writing-original draft preparation; M. Yetti: Methodology, data collection and validation, writing-original draft preparation; B. Hadisujoto: Conceptualization, methodology, validation, supervision; O.A. Juniasih: Validation, data curation, writing-original draft preparation, reviewing and editing; A. Azhari: Validation, writing-reviewing and editing.

## CONFLICTS OF INTEREST

The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its submission and declare no conflict of interest in the manuscript.

## REFERENCES

[1] P. Ding, X. Huang, S. Li, C. Zhao, and X. Zhang, "Real-time reliability analysis of micro-milling processes considering the effects of tool wear", *Mechanical Systems and Signal Processing*, vol. 200, pp. 1–25, 2023.

[2] L. O'Toole, C.-W. Kang, and F.-Z. Fang, "Precision micro-milling process: state of the art", *Advances in Manufacturing*, vol. 9, pp. 173–205, 2021.

[3] N. Kshirsagar and R. M. Tayade, "A review of sequential micro-machining: State of art approach", *Materials Today: Proceedings*, vol. 72, pp. 1394–1400, 2023.

[4] B. Z. Balázs, N. Geier, M. Takács, and J. P. Davim, "A review on micro-milling: recent advances and future trends", *The International Journal of Advanced Manufacturing Technology*, vol. 112, pp. 655–684, 2021.

[5] D. Axinte, H. Huang, J. Yan, and Z. Liao, "What micro-mechanical testing can reveal about machining processes", *International Journal of Machine Tools and Manufacture*, vol. 183, pp. 1–27, 2022.

[6] G. Liu, M. R. Karim, M. H. Arshad, K. K. Saxena, W. Liang, and H. Tong, "Tooling aspects of micro electrochemical machining (ECM) technology: Design, functionality, and fabrication routes", *Journal of Materials Processing Technology*, vol. 320, pp. 1–33, 2023.

[7] B. B. Barik, A. Mahanty, S. D. Majumder, and A. Roy Goswami, "Fabrication of Cost-effective Three-axis portable mini-CNC milling Machine", *Materials Today: Proceedings*, vol. 93, no. 4, pp. 581-588, 2023.

[8] V. C. Agbakoba, P. Hlangothi, J. Andrew, and M. J. John, "Mechanical and Shape Memory Properties of 3D-Printed Cellulose Nanocrystal (CNC)-Reinforced Polylactic Acid Bionanocomposites for Potential 4D Applications", *Sustainability*, vol. 14, no. 19, pp. 1-19, 2022.

[9] A. Andoko, R. Wulandari, R. Prasetya, R. P. Jeadi, and D. R.

Pradica, "Simulation of CNC milling 5 axis with finite element method," in 1st International Seminar on Advances In Metallurgy And Materials (i-SENAMM 2019) Jakarta, Indonesia, 2020, pp. 1–6.

[10] Z. Jamaludin, A. Sudianto, A. Mat Seman, A. Othman, M. Maharof, and S. H. Yahaya, "Performance Analysis of A CAD/CAM-Matlab/Simulink Interpreter in Milling Machine Application", *Journal of Advanced Manufacturing Technology*, vol. 17, no. 3, pp. 143-155, 2023.

[11] K. Saptaji, F. Triawan, T. K. Sai, and A. Gebremariam, "Deburring Method of Aluminum Mould Produced by Milling Process for Microfluidic Device Fabrication", *Indonesian Journal of Science and Technology*, vol. 6, pp. 123–140, 2021.

[12] J.-P. Hung, W.-Z. Lin, K.-D. Wu, and W.-C. Shih, "Analyzing the Dynamic Characteristics of Milling Tool Using Finite Element Method and Receptance Coupling Method", *Engineering, Technology & Applied Science Research*, vol. 9, no. 2, pp. 3918-3923, 2019.

[13] M. R. Fikri, K. Saptaji, and F. N. Azmi, "Wireless Vibration Monitoring System for Milling Process", *Journal of ICT Research and Applications*, vol. 16, no. 1, pp. 38–55, 2022.

[14] S. M. Ali and H. Mohsin, "Design and Fabrication of 3-Axes Mini CNC Milling Machine", *IOP Conference Series: Materials Science and Engineering*, vol. 1094, pp. 1–14, 2021.

[15] I. Santosa, A. Ridho, and G. R. Wilis, "Simulasi Kekuatan Mekanis Meja dan Frame Axis Sumbu-Z pada Mesin Router CNC Frais 3 Axis", *Teknika*, vol. 7, no. 3, pp. 140–151, 2022.

[16] P. Dunaj, B. Powałka, S. Berczyński, M. Chodźko, and T. Okulik, "Increasing lathe machining stability by using a composite steel–polymer concrete frame", *CIRP Journal of Manufacturing Science and Technology*, vol. 31, pp. 1–13, 2020.

[17] W. Chen, X. Teng, D. Huo, and Q. Wang, "An improved cutting force model for micro milling considering machining dynamics", *The International Journal of Advanced Manufacturing Technology*, vol. 93, pp. 3005–3016, 2017.

[18] T. Heitz, N. He, N. Chen, G. Zhao, and L. Li, "A review on

dynamics in micro-milling", *The International Journal of Advanced Manufacturing Technology*, vol. 122, pp. 3467–3491, 2022.

[19] P. Li, "The maintenance of ball screw of CNC machine," M.S. thesis, Department of Mechanical Engineering, Politechnic University of Turin, Turin, Italy, 2019.

[20] S. Arefin, X. Zhang, D. W. K. Neo, and A. S. Kumar, "Effects of cutting edge radius in vibration assisted micro machining", *International Journal of Mechanical Sciences*, vol. 208, pp. 1–15, 2021.

[21] Y. Zhang, Z. Yuan, B. Fang, L. Gao, Z. Chen, and G. Su, "Study on the Mechanism of Burr Formation by Simulation and Experiment in Ultrasonic Vibration-Assisted Micromilling", *Micromachines*, vol. 14, no. 3, pp. 1–16, 2023.