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Structure Analysis of Micro-Milling Machine Construction Frame Design

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Abstract — *Extreme precision and accuracy dimension with high quality of surface layer of product produced by the micro-milling machine is very important; hence the Structure of the micro-milling machine should be rigid and sturdy enough to withstand the force acting on the Structure when the machine operates. In this research, the objective is to design the micro-milling machine structure frame and to conduct static structural and modal analysis on the designated structures. Three micro-milling machine structure designs were proposed and compared in terms of the finite element analysis using ANSYS software, and the material used for the structures is Aluminum 7075-T6. The natural frequency and mode shape of the structures were analyzed, and the results are shown for the first mode shape for Structure A amount to* 363.97 *Hz which is higher than that of Structure B,* 278.96 *Hz and Structure C,* 252.54 *Hz. Hence, it can be concluded that Structure A has been chosen as the best design since Structure A has the highest natural frequency among those three structures.*

Keywords — *Design, modal analysis, mode shape, micro-milling machine, static structural analysis*

I. INTRODUCTION

Nowadays, there are a lot of machine structures that had been designed. These machine structures consist of their own characteristics that fulfill the requirements or the needs to function in the best condition [1]. The production of mechanical components with manufactured features in a range of microns is today's demand for the miniaturization of devices [2,3,4]. The micro-milling machine has static and dynamic behavior of the machine structure that had to be analyzed and developed, and it is important to sustain required accuracy, reliability, and productivity [5,6,7,33,35]. Micro-machining has become increasingly popular in the manufacturing industry. This goes for micro-milling as well [8,9,10,31].

In this research, the existing micro-milling machine that was developed and analyzed by a previous group of researchers needed external support to operate. The machine structure of the existing micro-milling machine needed external support, which indicates that the Structure is no longer rigid enough to withstand the static and dynamic forces acting on it [11,12,13,14].

Therefore, the structure frames of the micro-milling machine are designed. The static and dynamic behavior of the machine structures are analyzed, and the optimum Structure is then chosen as the micro-milling machine structure frame. The objectives of this research are to design the structure frames for the existing micro-milling machine using SolidWorks software, to investigate the Structure A, B, and C for replacing the current micro-milling machine structure frame, and lastly to analyze the designated structure frames of the existing micro-milling machine using ANSYS software. The basic idea of this FEM is actually to find the solution to a complicated structural problem by replacing the problem with a simpler structure [15,16,17,18].

The significance of the study is to be able to design and analyze the structural frame of the micro-milling machine. With the usage of SolidWorks 2018, the structure frames of the machine are able to be designed. The static and dynamic analysis of the Structure is able to be determined with the help of finite element analysis where ANSYS software is used [19,20,21,22]. This can help in analyzing the rigidity of the structure frames, and it will be easier to choose the optimum structure frame for the micro-milling machine [23,24,25,26].

This study can help in comparing designs for the micro-milling machine. Regarding the design of the machine structure, economic and environmental considerations are essential where overdesigned and less optimum performance and reliability are not tolerated. Therefore, this study can fulfill the demands made by the consumer, which are less vibration, lower cost, and high efficiency when operating. Figures 1 and 2 show the existing Micro-Milling Machine.

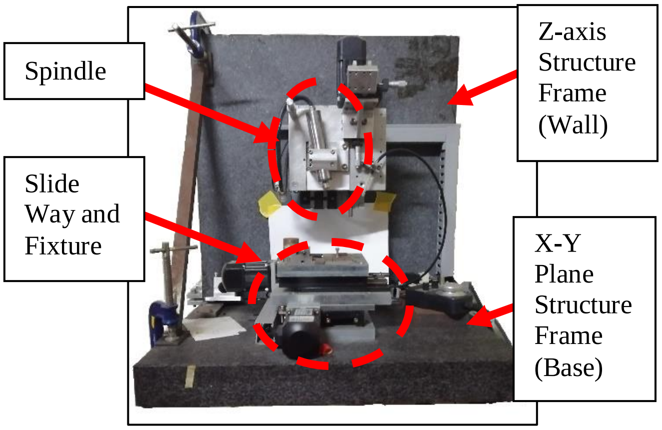


Figure 1: Front view of existing Micro-Milling Machine

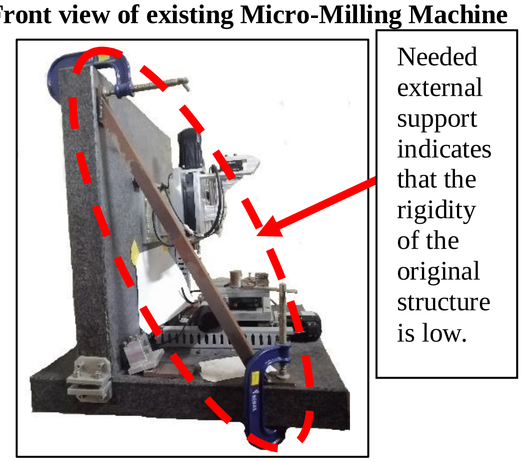


Figure 2: Side view of existing Micro-Milling Machine

II. MATERIALS AND METHODS

In order to design and analyze the micro-milling machine structure, the material for the structure frames is set, and the steps involved in choosing the suitable Structure for micro-milling start with designing the Structure followed by analyzing the Structure then choosing the best design. The newly designed structures are analyzed and compared using static structural analysis and modal analysis in ANSYS software [32,34].

A. Materials

Aluminum 7075-T6 has been chosen as the fixed material for the designated structure frames. This is because Aluminum 7075-T6 is said to be used where high strength is critical and where good corrosion resistance is not important [27].

B. Methods

The structures are named Structure A, B, and C, which are shown in Figures 3, 4, and 5. Structure A (i) is based on the vertical milling machine, whereas Structure B (ii) is based on the desktop milling machine, and lastly, Structure C (iii) is based on a bridge-type milling machine. The conceptual design of all the structures is the base of the Structure is set to $500\ mm \times 500\ mm$. The volume of the models are set to $0.0216\ m^3$ each so that the design of the Structure can be compared. The meshing of the structures are set to $2 \times 10^{-2}\ m$ of its element size and the node shape is set to tetrahedron shape.

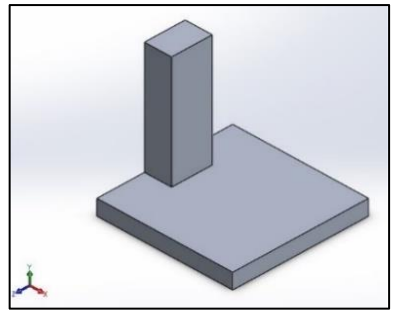


Figure 3: Structure A

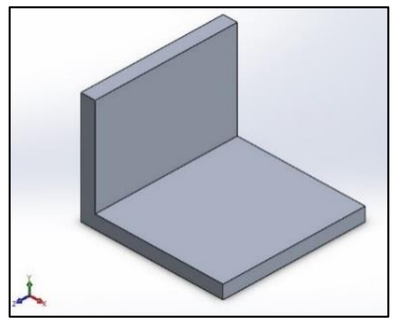


Figure 4: Structure B

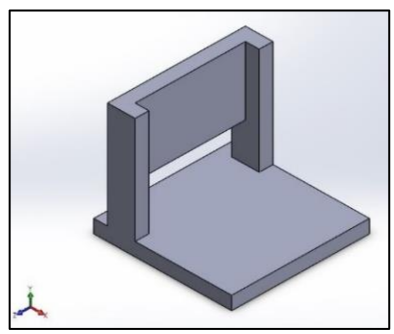


Figure 5: Structure C

The shapes for all three structures can be differentiated by the size of the wall or arm of the structures. Structure A uses a single arm to support the spindle, whereas Structure B uses a wall. However, Structure C uses two arms to support the spindle and the wall that will use to connect the spindle onto the Structure.

For static structural analysis, there are three (3) types of analyses, which are without force, standard earth gravity, and with force, 50 N and 100 N. When analyzing all of the three (3) designated structures, there are two (2) boundaries that are very crucial for the static structural analysis. The types of the boundary are the fixed support of the Structure and the presence of the standard earth gravity on the Structure. Figure 6 shows the fixed support, whereas Figure 7 shows the standard earth gravity.

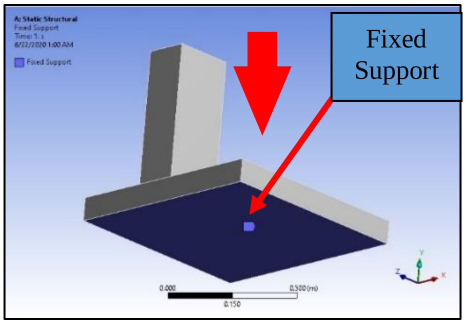


Figure 6: Fixed support for static structural analysis

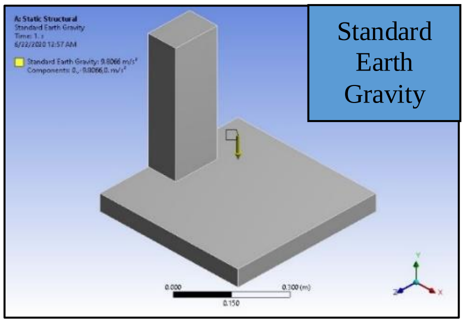


Figure 7: Standard earth gravity

First of all, for the fixed support, since the structural frame of the micro-milling machine would be stationary, it is certain that the Structure would have fixed support at the bottom surface of the Structure. Other than that, the boundary that is set for the Structure is the standard earth gravity. This is because when the Structure is manufactured, the Structure will experience gravitational earth pull even when the machine is not operating. The value of the standard earth gravity is 9.8066 m/s^2 And the direction the gravitational pull acting on the structures is at negative y-axis direction.

In order to determine the rigidity of the three (3) designated models, 50 N and 100 N of forces are applied at negative X, Y, and Z-axis directions. 50 N and 100 N of forces are applied separately in order to measure the deformation of the structures when the force is acting on the structure increases. The force is applied in 3 different directions. Figures 8, 9, and 10 show 50 N of force acting on the arm of the Structure at the negative x-axis, y-axis, and z-axis direction, respectively.

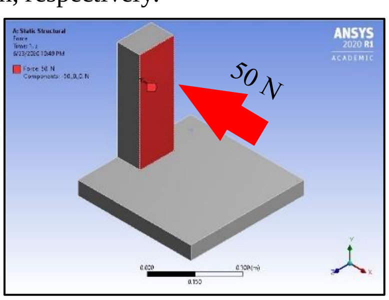


Figure 8: 50 N of force acting on the arm of the Structure at the negative x-axis

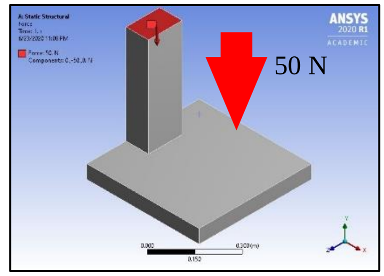


Figure 9: 50 N of force acting on the arm of the Structure at the negative y-axis

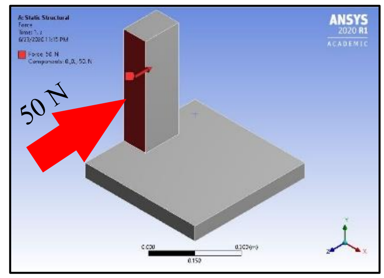


Figure 10: 50 N of force acting on the arm of the Structure at negative z-axis

For modal analysis, only theoretical modal analysis is carried out in this study. There is only one boundary condition for the modal analysis, which is the fixed support. The fixed support is set at the bottom surface of the Structure because after the structure frame is manufactured, the base will be fixed onto the table.

III. RESULTS AND DISCUSSION

The designated structures are analyzed and compared in order to select the best Structure for the current micro-milling machine. The analyses involved are static structural analysis and modal analysis. These analyses are suitable for analyzing the rigidity of the Structure, especially for the machine frame.

For static structural analysis, the analysis without force and with force, 50 N and 100 N are carried out. The graphs below show the results of total deformation for static structural analysis.

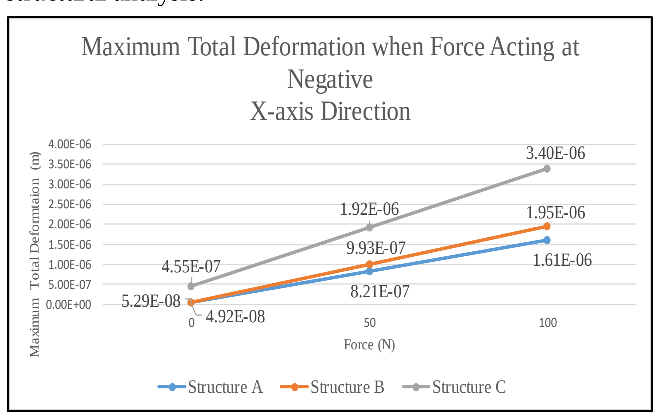


Figure 11: Graph for negative x-axis direction

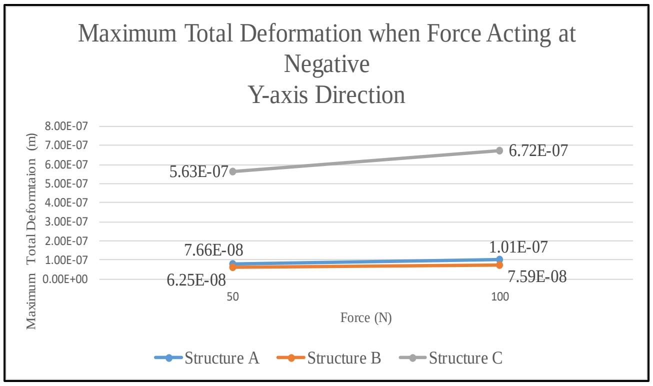


Figure 12: Graph for negative y-axis direction

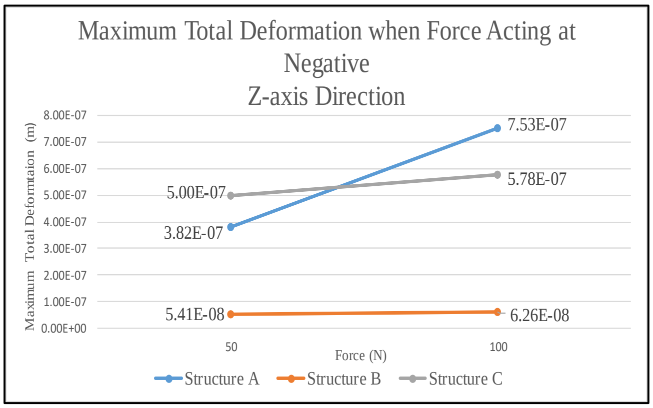


Figure 13: Graph for negative z-axis direction

The results show that Structure C deformed the most. This means that Structure A and B are more reliable than Structure C when there are forces acting on the Structure at a negative x-axis direction. The smaller the total deformation formed by the Structure, the more reliable the Structure is when operating the machine [28,29].

From the graph above, the maximum total deformation for Structure A and B are relatively lower than that of Structure C. Structure C shows very large differences compared to other structures. The differences of the deformation when only subjected to the gravitational force between Structure C, the highest displacement of the Structure and Structure B, which has the lowest displacement is $4.05597 \times 10^{-7}\ m$. For 100 N force when applied to the Structure, the differences between the highest, Structure C and the lowest deformation, Structure A, is $1.7893 \times 10^{-8}\ m$. This means that Structure A and B are more reliable than Structure C when there are forces acting on the Structure at a negative x-axis direction. According to Nyein Chan et al. (2019), the smaller the total deformation formed by the Structure, the more reliable the Structure is when operating the machine [29].

The maximum stress produced by Structure A, B, and C are $98\ MPa$, $77\ MPa$, and $210\ MPa$ respectively, whereas the maximum yield strength of the material is $503\ MPa$. All of the structures produce lower equivalent stress than the maximum yield strength of the material, which means that the structures would not break down upon operating. Figures 14, 15, and 16 show the total deformation when structures A, B, and C are subjected to standard earth gravity without external force, respectively.

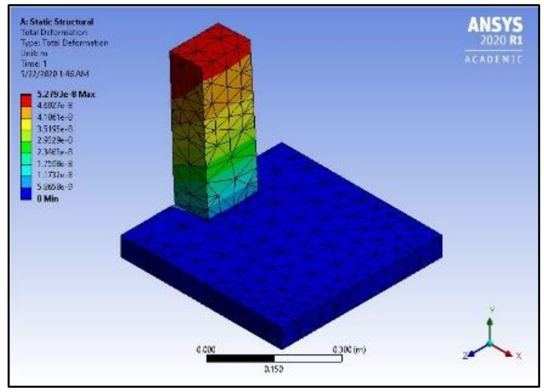


Figure 14: Total deformation of Structure A (Gravity)

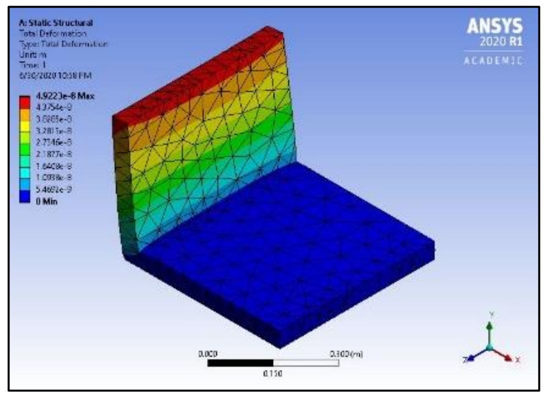


Figure 15: Total deformation of Structure B (Gravity)

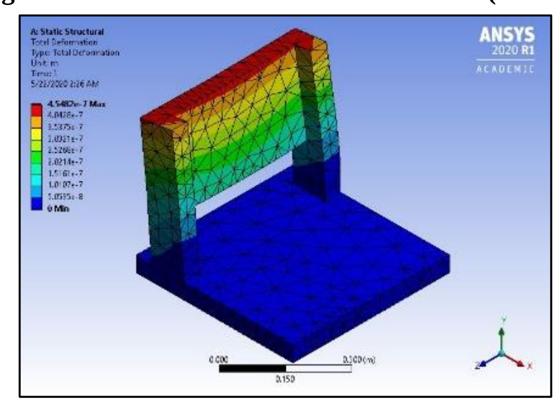


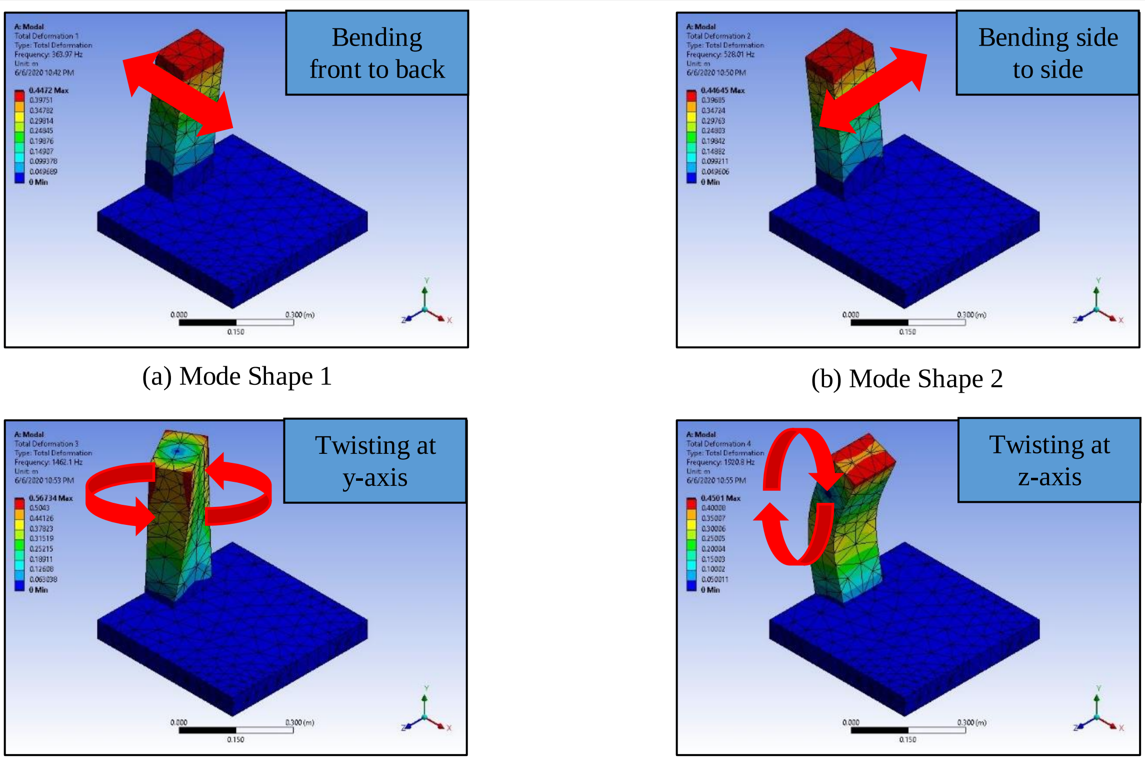
Figure 16: Total deformation of Structure C (Gravity)

Since the experimental analysis for the Structure cannot be carried out, the results are compared with other similar research so that the results obtained in this research can be validated. From the previous research done by Hassan et al. (2014), the maximum total deformation formed by both of the researcher's Structure, Design A and Design B, are $6.2675 \times 10^{-4}\ mm$ and $2.7142 \times 10^{-4}\ mm$ respectively when 100 N force is applied at the y-axis to the structures. Design B was chosen as the best design and has been already validated with the modal analysis, which means that the deformation formed by the Structure is acceptable.

In this thesis, the y-axis direction of the force is at the x-axis direction, which means that the results that will be compared is when the force of 100 N is applied at the x-axis direction. The first Structure, Structure A, shows $1.6096 \times 10^{-4}\ mm$ whereas Structure B, $1.9472 \times 10^{-4}\ mm$ and lastly Structure C, $3.3989 \times 10^{-4}\ mm$. All of the values for the displacement of the structures at the x-axis direction are $\pm 0.0001\ mm$ of the previous journal chosen design.

The mode shape and the total deformation of Structure A, B, and C are analyzed. Figure 17 shows the mode shape 1, 2, 3, and 4 of Structure A. Figure 18 shows the mode shape 1, 2, 3, and 4 of Structure B, whereas Figure 19 shows the mode shape 1, 2, 3, and 4 of Structure C.

The graphs in Figure 20 shows the graph for the natural frequency of all the structures. The results show that the natural frequency for Structure A is higher than that of Structure B and Structure C. For mode shapes 1, 3, and 4, Structure A shows a higher natural frequency than that of Structure B, whereas only in mode shape 2 that Structure B show a slightly higher natural frequency, and lastly, Structure C shows none. The minimum natural frequency of the structure is based on the mode shape 1 of the Structure. This means that Structure A has a higher natural frequency than Structure B, which is $79.85\ Hz$ more and when compared with Structure C is $111.43\ Hz$. The results show that Structure A has higher stiffness of the machine structure, which indicates that the dynamic performance of Structure A is better than that of Structure B and Structure C [7,5,30].



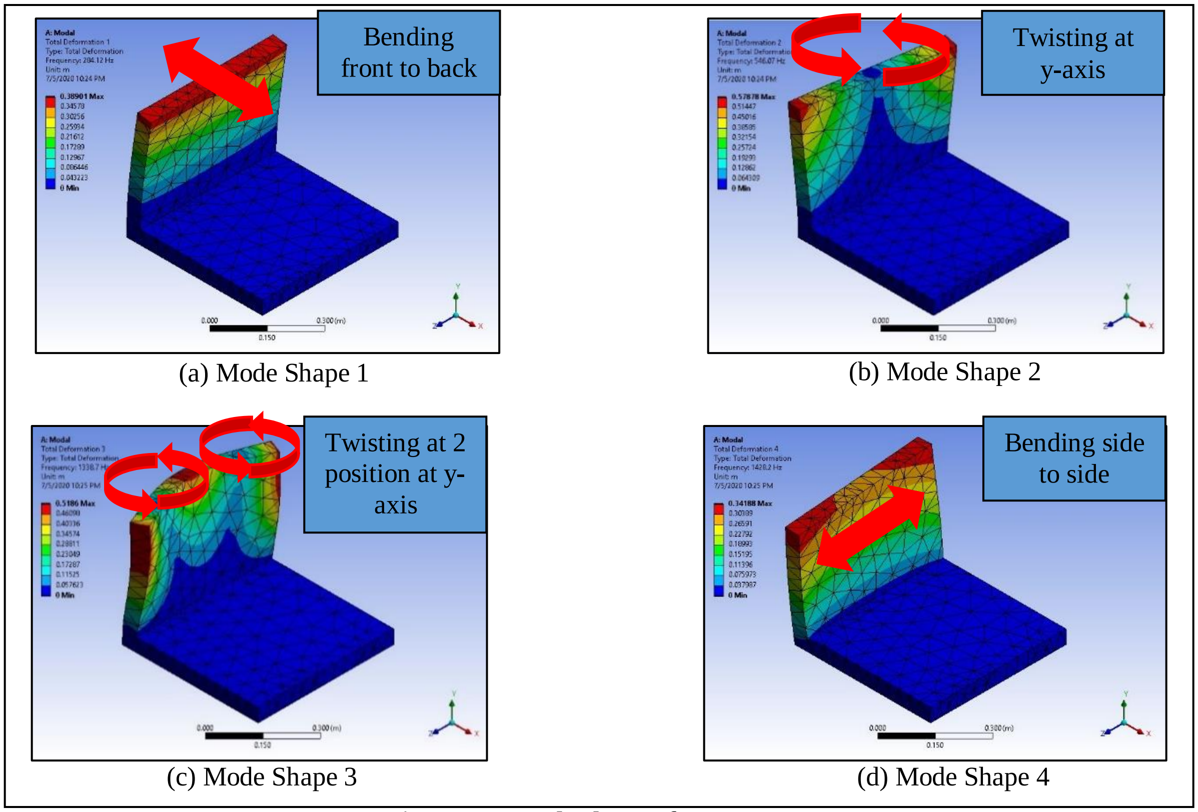
(a) Mode Shape 1

(b) Mode Shape 2

(c) Mode Shape 3

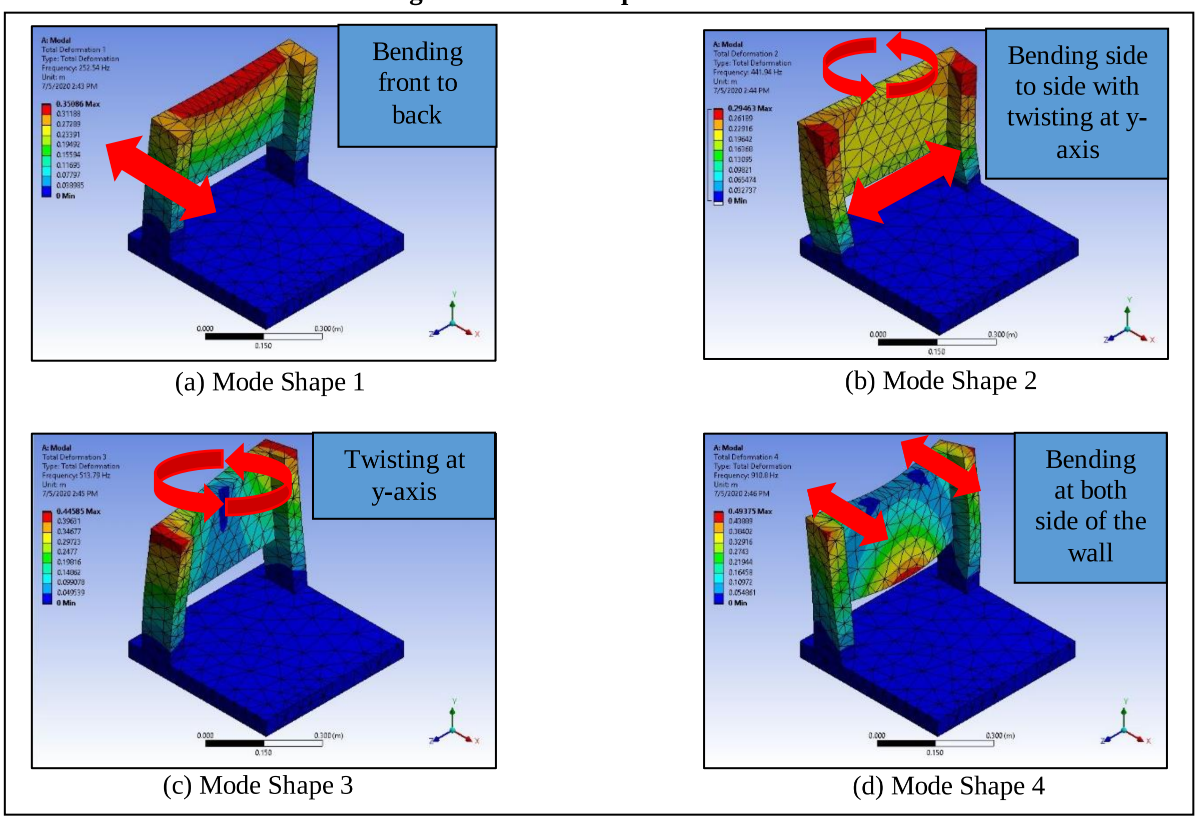
(d) Mode Shape 4

Figure 17: Mode shape of Structure A



(a) Mode Shape 1 (b) Mode Shape 2 (c) Mode Shape 3 (d) Mode Shape 4

Figure 18: Mode shape of Structure B



(a) Mode Shape 1 (b) Mode Shape 2 (c) Mode Shape 3 (d) Mode Shape 4

Figure 19: Mode shape of Structure C

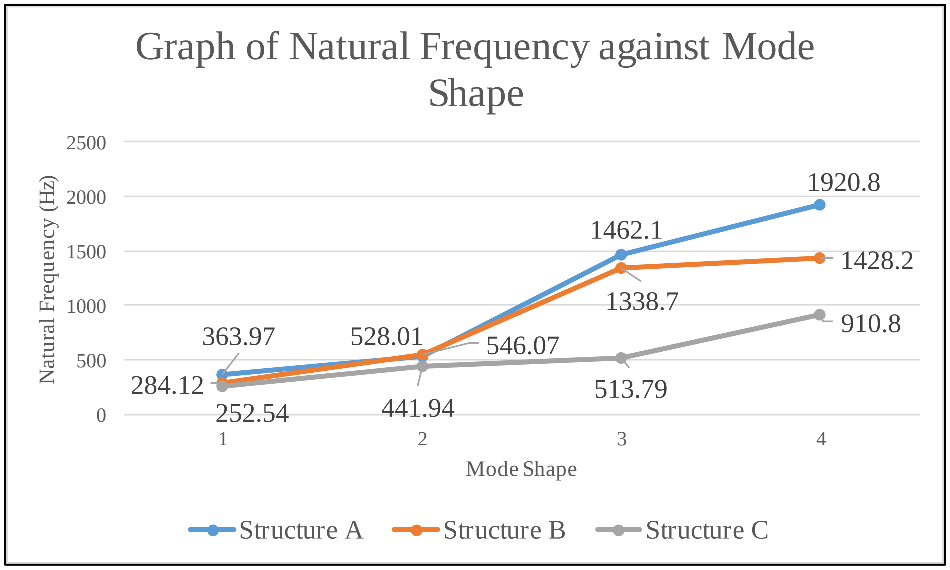


Figure 20: Graph of natural frequency against mode shape

IV. CONCLUSIONS

In conclusion, Structure A shows the highest natural frequency among all of the designated structures. Structure A has higher stiffness of the machine structure, which indicates that the dynamic performance of Structure A is better than that of Structure B and C. Therefore, it is concluded that the best design that is suitable for the existing micro-milling machine is Structure A.

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