INVESTIGATION OF THE CHANGE OF VIBRATION IN CARTESIAN 3D PRINTER SYSTEMS WITH MECHANICAL IMPROVEMENTS AND ITS EFFECTS ON SURFACE ROUGHNESS

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Abstract

3D printers are widely used in every industry these days. However, the features required from the products are becoming more and more important. Especially in the field of prototyping, 3D printers have become indispensable in design and manufacturing. One of the most important factors determining the product quality is the surface quality. Also, the most important factor determining the surface quality in production is the robustness of the production machine. Therefore, a 3D printer with a Cartesian system, which is the most widely used mechanical system, was chosen in this study. A production sample in the shape of a cube was preferred and a total of nine different parameters were used at three different printing speeds (40, 60, 80 mm/sec.) and three different filling forms (hilbert curve, octagram spiral, concentric). The standard system vibrations of this printer were recorded with the help of dataloggers that measure 3-axis acceleration during production. Afterwards, mechanical improvements were made in the system in all 3 axes. After these improvements, the same production process was carried out again and the difference in mechanical vibrations in the system was examined. In addition, in order to observe the change in the production quality, the surface roughness values in each production were examined in 3 axes and the changes in the production quality were examined. Mechanical improvements provide quality increase in every axis on the surface quality. However, when compared with the measured vibration values, there is no significant correlation between them. As a result, it can be said that the rigidity feature in 3D printer mechanical system has a great effect on the product properties and quality.

Keywords: *3D printing, Surface roughness, mechanical vibration*

1. INTRODUCTION

Today, additive manufacturing has become indispensable in many sectors such as traditional manufacturing methods. For this reason, it is aimed to maximize the quality limits of the obtained products [1]. When determining the quality of the product in additive manufacturing methods, basically two main features are considered. The first of these factors is the mechanical properties [2]. However, since the main material used in the additive manufacturing method is plastic material, it is generally preferred for the production of functional products, not for mechanical properties. The other quality feature is surface quality. This quality feature is one of the main quality elements of production in all other manufacturing methods [3]. In general, surface quality and other quality characteristics show variable behavior depending on the production parameters. For this reason, it is tried to determine the best production parameters in order to increase the quality in general [4]. On the other hand, modifications and revisions are made in the production system in order to improve the quality characteristics obtained in the desired production parameters. System improvements in general aim to increase its rigidity. The effects of the revisions made in the system on the rigidity are generally controlled by measuring the system vibrations. In many areas, parameters such as vibration, load and temperature are controlled during production and it is monitored whether the desired quality characteristics are achieved or not. When the studies on vibration measurement and quality control in the additive manufacturing method are examined, a vibration measurement stand was developed with the help of an optical sensor and tests were made to predict the mechanical properties of the product by making controls during additive manufacturing [5]. In another study, it was aimed to minimize the waste material and time caused by faulty production by means of a machine learning algorithm developed by measuring vibration data during additive manufacturing in order to detect defects during production [6]. In a review study on the examination of vibrations occurring during additive manufacturing, it was stated that vibrations during production have a great impact on the quality of production and that these vibration elements vary depending on parameters such as printer type, nozzle type, production speed and filling method [7]. The type and production method of the printers is a parameter that is of great importance in terms of vibration and production quality. If we look at the current literature studies on this subject, they calculated the natural frequencies of different systems using the Euler-Lagrange method, based on the different designs of the most reliable and inexpensive Cartesian 3D printer systems today. Thus, they aimed to assist printer designers to produce more rigid designs [8]. In the other study, modal analysis was performed using Fusion 360 software to obtain the natural frequency and associated displacement values of Anycubic i3 Mega brand and model gantry printer. Thus, they investigated the vibration accuracy in high speed productions [9]. In another study, system vibrations were obtained by attaching a gyroscope accelerometer to a robot arm with a gantry system, similar to additive manufacturing machines. In addition, the natural frequency and modes of the system were analyzed using the finite element method. Then, they tested different situations by changing the distance between the holder and the arm and the connection points. Solidworks finite element simulation and theoretical results offer very close values. It has been observed that the vibrations of the system in the first and second modes are high. Thanks to the revisions made, these values were improved and the system was developed [10]. Another of the issues examined in relation to vibration in the additive manufacturing method is the state of the nozzle and its positioning. If we refer to some studies in the literature on this issue, they examined the situation where the filament material feed and the nozzle are adjacent. They examined the case where the filament feed and nozzle were separate. They used flexible, Acrylonitrile ButadieneStyrene (ABS) and Polylactic acid (PLA) materials for both conditions. As a final condition, they obtained the vibration data with an accelerometer attached to the nozzle by experimentally realizing the cases where the nozzle was clogged. As a result, it was suggested that the nozzle condition can be followed by vibration measurement [11]. If studies on vibration and product quality are examined, vibration data is generally analyzed in relation to surface roughness measurement and tensile strength. As an example, the table vibration was measured during production with a 3D Kreator Motion printer and the roughness values in the Z direction of the glass-shaped sample were measured. As a result, it is said that the surface quality affects the vibration values and quality in relation to the production speed [12]. In another study, accelerometer sensors were attached to the platter and nozzle to examine the relationship between vibration and surface roughness. The natural vibration frequency and modes of the system are calculated. Afterwards, productions were made in the vibration-free condition of the sample printer, in the condition where vibration was applied to the printer with the help of a vibrating table from the bottom, and when dampers were applied together with the vibration. As a result, an example of a damping system for vertically applied vibrations is given. They have tried to apply this system to use when additive manufacturing production is required, generally on ships and in places where the movement is under difficult conditions [13]. In a separate study, tensile test specimens were produced with Polyethylene terephthalate glycol (PET-G) material with three different printing speeds and two different angle orientations of rectilinear fill shape. During these productions, vibration measurements were made with the help of accelerometers in three movement axes. It is understood from this study that the low printing speed and the decrease of the slope in the tool path rotations reduce the vibration amplitude [14]. In another study, the surface quality of the samples produced by choosing the filling shapes and the number of filled top layers as variable parameters was examined. It was stated that the honeycomb filling method and three filled top layers gave better results in terms of surface quality and vibration [15].

As in every manufacturing method, quality and mechanical vibrations are closely related concepts in additive manufacturing. When the literature is examined, since the additive manufacturing method is a much newer field compared to other manufacturing methods, the relationship between quality and mechanical vibrations in this field has not yet been systematically clarified. In studies dealing with vibration in general, the natural frequencies of 3D printer systems or the vibration measured during production and the surface roughness in only one axis direction are discussed. Especially in many studies, surface roughness was measured in the Z axis. In addition, the effect of mechanical improvements, which are widely used as system improvement, on surface quality and system vibrations has not been examined in the literature. For these reasons, it is aimed to show the users and manufacturers how the system improvements affect the surface quality and how the vibration is affected with system improvements.

2. MATERIALS AND METHODS

2.1. Materials

In the study, the Ender 3 Max model was preferred as a 3D printer with a widely used gantry system. This 3D printer uses a 3-axis cartesian motion system. If we list the basic features, the print size is 300x300x340 mm, the stable printing speed is 30 – 60 mm/sec, the layer thickness is 0.1 – 0.4 mm, the printing accuracy is ± 0.1 mm. In Figure 1 below, the printer used in the study before the mechanical improvements and the coding for the three axes are given.

Fig. 1. 3D printer and coding of working axes

In the study, ABS material was used as the most preferred filament material. The general properties of the materials are given in Table 1 below.

Properties	Values
Density (g/cc)	1.12
Moisture Absorption (%)	0.35
Melt Flow (g/10 min)	9-14
Hardness (Shore D)	72
Modulus of Elasticity (GPa)	1.835
Flexural Modulus (GPa)	2.844
Charpy impact, Notched (J/cm^2)	1.05
Crystallization Temperature (°C)	113.5
Vicat Softening Point (°C)	103.9
Glass Transition Temperature, Tg (°C)	101.1

Table 1. General properties of ABS filament material [16]

Source: MatWeb, Material Property Data, Polymaker PolyLite™ ABS 3D Printing Filament data, July 2023.

Among the factors affecting the product properties in the additive manufacturing method, the printing parameters are as influential as the material. In Table 2 below, the parameters that are kept constant and determined as variables are given as printing parameters.

Parameters	Values
Layer thickness (mm)	0.2
Cooling fan (-)	Disable
Filling rate (%)	30
Nozzle diameter (mm)	0.4
Top solid layer (-)	3
Perimeter number (-)	3
Nozzle temperature (°C)	225
Table temperature (°C)	85
Printing speed (mm/sec)	40 - 60 - 80
Travel speed (mm/sec)	130
Filling form (-)	Concentric Octagram spiral Hilbert curve

Table 2. Specified 3D printing parameters in this study

The filling form parameter given in Table 2. was chosen as a variable printing parameter within the scope of the study. These filling forms affect the surfaces and vibration behavior by creating different infill forms in the sample internal structure and changing the path followed by the nozzle. Filling forms are given in Figure 2 for a better understanding of the sample surfaces.

Fig. 2. Filling forms a) Concentric b) Octagram spiral c) Hilbert curve

Additional parts were purchased for each movement axis for mechanical system improvements. These parts are sold as improvement opportunities provided by the original manufacturer. A tensioning mechanism was applied to the belt system used for the X-axis movement, a tensioning mechanism to the belt system for the Y-axis movement, and a second trapezoidal screw system was applied as an improvement to the axes, since the Z-axis movement was by trapezoidal screw. Pictures of these mechanical improvement parts added to the system are given in Figure 3.

Fig. 3. Mechanical improvement parts a) X axis tensioner b) Y axis tensioner c) Dual Z axis trapez screw

2.2. Methods

In the additive manufacturing process, it is aimed to show the effect of systemic improvements to users and manufacturers by analyzing the relationship between surface quality and mechanical system improvements available in the market as standard. Therefore, variable parameters such as printing speed and filling form parameters, which are the 3D printing parameters that affect vibration and tool path movement the most, were chosen. Before mechanical improvements, 9 calibration cubes of 20x20x20 mm were produced with 3 different printing speeds (40, 60, 80 mm/sec) and 3 different filling forms (concentric, octagram spiral, hilbert curve) given in Figure 2. All 9 different calibration cubes were produced under exactly the same conditions and with the same production codes, after mechanical system improvements. Table 3 shows the experimental setup and sample coding. Cases with 1 as the first number refer to samples produced before mechanical improvements. The ones denoted with 2 at the beginning refer to the samples produced after mechanical improvements.

Sample No	Printing Speed (mm/sec)	Filling Form
1.1.	80	Octagram spiral
1.2.	60	Octagram spiral
1.3.	40	Octagram spiral
1.4.	80	Hilbert curve
1.5.	60	Hilbert curve
1.6.	40	Hilbert curve
1.7.	80	Concentric
1.8.	60	Concentric
1.9.	40	Concentric
2.1.	80	Octagram spiral
2.2.	60	Octagram spiral

2.3.	40	Octagram spiral
2.4.	80	Hilbert curve
2.5.	60	Hilbert curve
2.6.	40	Hilbert curve
2.7.	80	Concentric
2.8.	60	Concentric
2.9.	40	Concentric

Table 3. Experimental setup and sample coding in this study

2.2.1. Mechanical improvements

First of all, it is necessary to talk about axis drive systems before talking about axis improvements. Because the improvement according to this drive system and its effects on the system varies. When the axis driving methods and motion transmission methods in Cartesian 3D printers are examined, since low loads are carried and no load is reflected on the system, stepper motor and belt-pulley transmission on the X and Y axes is preferred for faster and smoother movements. Normally, in these systems, the belts are tensioned and attached in a constant manner. This installation process provides a non-standard tension with normal human power. Axis tensioning parts are available to better optimize and continuously control this. In our study, we have made improvements in these axes with tensioning systems for the transmission of motion with the belt in the X and Y axis. Since the Z axis carries loads and moves precisely with small steps, 3D printers provide motion transmission with a trapezoidal screw. Here, as an improvement, a second trapezoidal screw has been added to the opposite of the Z axis, thus preventing parallelism problems and vertical shifts during vertical movement in the Z axis. The axis improvements made in the Cartesian 3D printer and the status of the axes before the improvement are given in Figure 4.

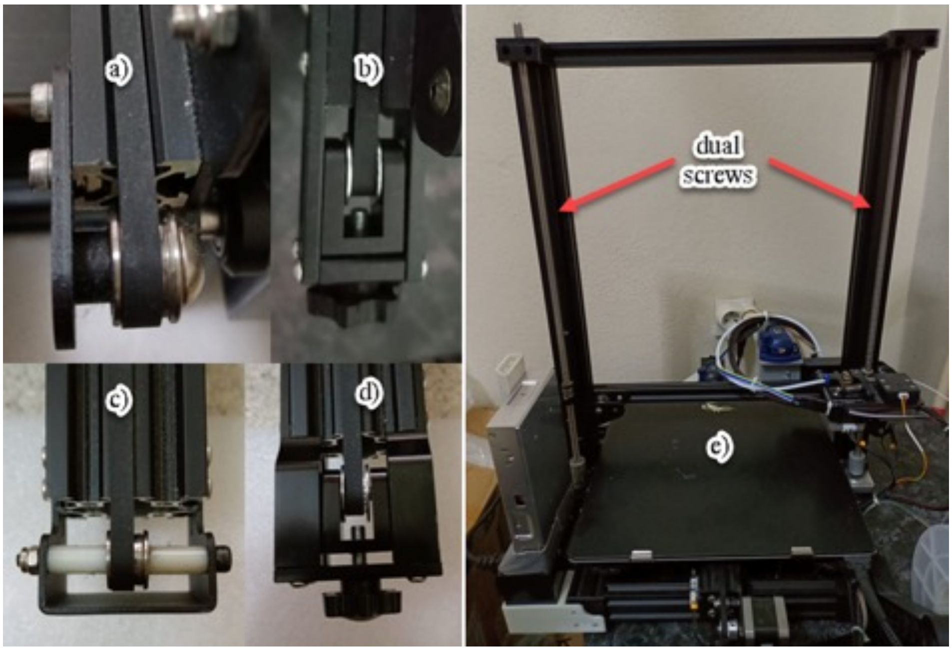

Fig. 4. Mechanical improvements for each axis a) Before installing the X-axis tensioner b) After installing the X-axis tensioner c) Before installing the Y-axis tensioner d) After installing the Y-axis tensioner e) After Z-axis dual trapezoidal screw installation

2.2.2. Vibration measuring

For vibration measurements, a 3-axis accelerometer was attached to the moving axes of the 3D printer and the changes that occurred during the production were recorded. In this system, the motion in the X direction and the motion in the Z direction are transmitted to the nozzle with the help of the carrier block. For this reason, a 3-axis accelerometer was attached to the block carrying the nozzle by producing an auxiliary part and vibrations in the X and Z directions were recorded during production. Since the movement in the Y direction is transmitted to the heating table, one connection part is produced and another 3-axis accelerometer is connected to the table with connection part. In this way, vibration values in the Y direction were recorded during production with this 3-axis accelerometer. In Figure 5, the places where the 3-axis accelerometers are connected and their connection types are given. PCE brand VD-3 model internal three-axis accelerometer datalogger has a measuring range of ±16 g and operates in the frequency range of 0 … 60 Hz.

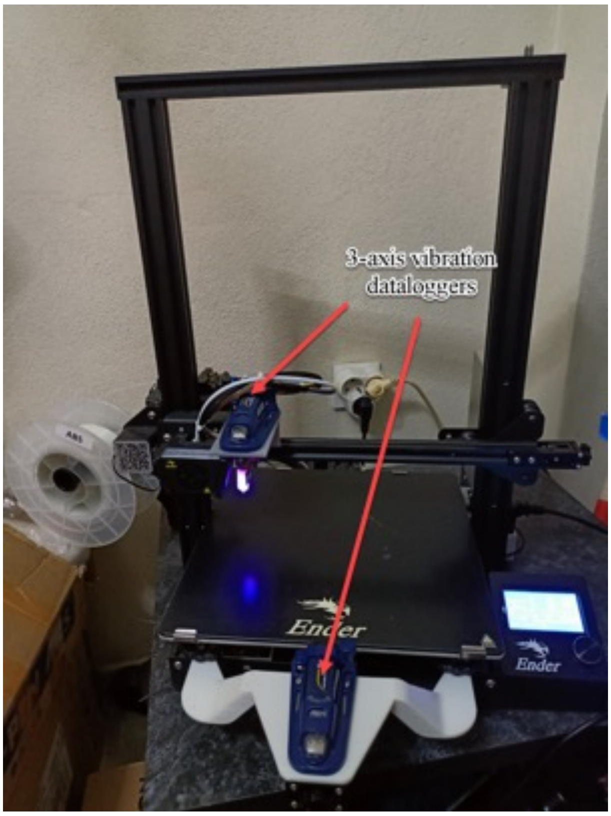

Fig. 5. Installation of 3-axis accelerometers in the system

2.2.3. Surface roughness measurements

After all productions were completed, the surface roughness values of all samples were measured three times from each axis Ra (average surface roughness) and average values were calculated. In Figure 6.a, the axes of the samples produced are indicated. Surface roughness values in X and Y directions were measured from the top surface. Afterwards, the roughness values in the vertical Z direction were measured by turning it sideways. In Figure 6.b, a picture is given during the surface measurements. As the surface measuring device, the Accretech brand Handysurf+ model portable surface roughness measuring device was used. All Ra measurements were made in accordance with the TS EN ISO 13565 standard.

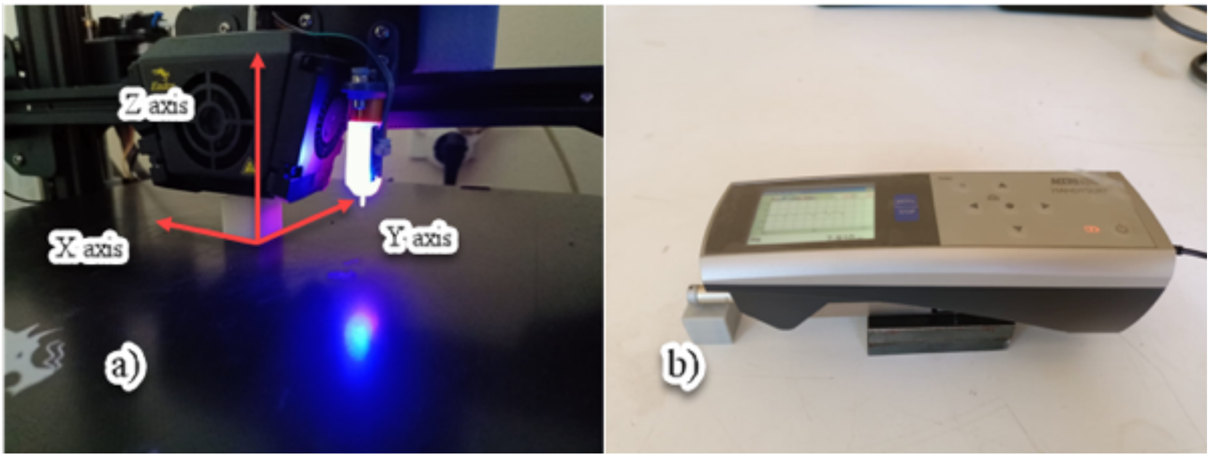

Fig. 6. a) Indication of the axes of the sample for surface measurement b) Surface roughness measurements

3. RESULTS AND DISCUSSION

3.1. Surface roughness measurement results

As the results of the study, surface roughness measurements on each axis and mechanical vibrations on each axis were measured. As stated in the experimental setup, 3D printing parameters effective on surface roughness and vibration were kept variable in the produced samples. In addition, mechanical improvements in each axis and their effects on quality and system vibration are studied. In Table 4, the surface roughness measurement values in each axis of the samples produced before and after mechanical improvement are given for each parameter.

Sample No	Printing Speed (mm/sec)	Filling Form	Along X axis	Along Y axis	Along X axis
1.1.	80	Octagram spiral	7.843	2.981	29.141
2.1.	80	Octagram spiral	3.737	2.739	25.115
1.2.	60	Octagram spiral	6.664	7.236	22.942
2.2.	60	Octagram spiral	3.456	5.153	18.125
1.3.	40	Octagram spiral	7.867	5.513	24.919
2.3.	40	Octagram spiral	4.835	5.551	20.853
1.4.	80	Hilbert curve	8.301	9.576	23.766
2.4.	80	Hilbert curve	5.504	7.910	22.871
1.5.	60	Hilbert curve	8.933	6.680	23.913
2.5.	60	Hilbert curve	9.063	6.876	20.171
1.6.	40	Hilbert curve	6.715	9.924	26.380
2.6.	40	Hilbert curve	7.177	5.144	23.797
1.7.	80	Concentric	7.553	5.451	22.372
2.7.	80	Concentric	5.657	6.476	20.479

1.8.	60	Concentric	9.431	5.920	22.302
2.8.	60	Concentric	4.770	6.866	20.742
1.9.	40	Concentric	5.084	5.300	21.771
2.9.	40	Concentric	5.015	5.080	20.422

Table 4. Averaged surface roughness measurement results (Ra - µm)

When Table 4 is examined, it can be said that the surface roughness values are positively affected at the end of the mechanical improvements in the measurements made for each production condition and in each axis. With the reduction of the printing speed, the surface quality increases and mechanical improvements also demonstrated positive results, but the degree of effectiveness decreases compared to high speeds. When the effect of the filling forms on the surface quality is examined, it is observed that the concentric filling form gives a slightly better surface quality because the tool path is more regular, even though there are no extreme differences. When the X and Y axes were compared, no significant differences were observed between them and it was observed that they exhibited similar surface quality. However, different behavior was exhibited in the Z axis as it formed the layer thickness on the vertical axis. A coarser surface roughness value was measured, since in the ideal case the layer thickness is 0.20 mm. However, printing speed reduction and mechanical improvements decreased the measured surface roughness values and showed improvement in surface quality.

3.2. Vibration measuring results

In order to examine the vibration effects of the mechanical improvements on the mechanical system and the relationship of these effects with the surface quality, vibration measurements were made on all axes throughout the production. These vibration measurements are arranged and the average, minimum and maximum vibration values in each axis are given in Table 5 for each production condition and before and after mechanical improvement.

Sample No	**Averaged Vibration Along X axis**	**Averaged Vibration Along Y Axis**	**Averaged Vibration Along Z Axis**	**Maximum Vibration Along X axis**	**Maximum Vibration Along Y Axis**	**Maximum Vibration Along Z Axis**	**Minimum Vibration Along X axis**	**Minimum Vibration Along Y Axis**	**Minimum Vibration Along Z Axis**
1.1.	-0.06	0.09	1.07	0.29	0.50	1.48	-0.48	-0.34	0.98
2.1.	-0.09	0.10	1.07	0.46	0.58	1.44	-0.59	-0.42	1.00
1.2.	-0.06	0.09	1.07	0.28	0.55	1.62	-0.46	-0.35	0.96
2.2.	-0.08	0.10	1.07	0.4	0.6	1.45	-0.6	-0.46	0.99
1.3.	-0.06	0.09	1.06	0.29	0.5	1.45	-0.4	-0.31	0.99
2.3.	-0.08	0.11	1.06	0.53	0.63	1.38	-0.6	-0.44	1.00
1.4.	-0.07	0.09	1.07	0.36	0.56	1.54	-0.64	-0.45	0.97
2.4.	-0.09	0.13	1.08	0.53	0.73	1.48	-0.7	-0.58	0.99
1.5.	-0.07	0.09	1.07	0.3	0.62	1.49	-0.61	-0.51	0.99

2.5.	-0.09	0.13	1.07	0.39	0.64	1.59	-0.59	-0.48	0.98
1.6.	-0.08	0.09	1.07	0.46	0.74	1.48	-0.57	-0.45	0.98
2.6.	-0.09	0.14	1.07	0.63	0.77	1.58	-0.6	-0.54	0.99
1.7.	-0.06	0.09	1.06	0.34	0.53	1.44	-0.4	-0.26	1.00
2.7.	-0.08	0.14	1.07	0.35	0.57	1.53	-0.5	-0.31	0.98
1.8.	-0.06	0.09	1.06	0.31	0.45	1.46	-0.42	-0.27	1.00
2.8.	-0.08	0.13	1.06	0.34	0.64	1.48	-0.52	-0.27	0.96
1.9.	-0.07	0.09	1.06	0.52	0.52	1.42	-0.51	-0.28	0.99
2.9.	-0.08	0.15	1.06	0.6	0.54	1.59	-0.46	-0.32	1.00

Table 5. Averaged maximum and minimum mechanical vibration results (g)

After the mechanical improvements, an absolute increase in the average vibration values calculated in the X and Y axes was observed in each production condition. As the reason for this, it can be said that there is some variability in the natural frequency values of the system, since the added parts increase the total mass of the system. On the Z axis, no change was observed on the calculated average vibration values associated with mechanical improvements. When Table 5 is examined for the minimum and maximum vibration values, very small absolute increases are seen, as in the calculated average vibration values. Apart from this, there were no changes that can be related to the surface roughness values and there was no proportional increase or decrease. Based on this, it can be thought that mechanical improvements provide an improvement on the surface quality by affecting the system rigidity rather than mechanical vibrations.

4. CONCLUSIONS

As a result, the effects of mechanical improvements on the surface quality of the gantry system cartesian printers used in 3D printing, which is widely used from additive manufacturing methods, and their relationship with system vibrations were investigated. According to this;

- Mechanical improvements give successful results on surface quality in all 3 axes.
- The effects of mechanical improvements on surface quality become greater as printing speed increases. It has an effect on slower print speeds, but it provides less improvement proportionally.
- When the effect of the filling forms on the surface quality is examined, it is observed that the concentric filling form gives a slightly better surface quality because the tool path is more regular than other filling forms.
- After the mechanical improvements, an absolute increase in the average, maximum and minimum vibration values calculated in the all axes was observed in each production condition. As the reason for this, it can be said that there is some variability in the natural frequency values of the system, since the added parts increase the total mass of the system.
- After the mechanical improvements, there was no change that could be related between the surface roughness values and the calculated vibration values, and there was no proportional increase or decrease. From this point of view, it can be thought that mechanical improvements improve the surface quality by affecting the system rigidity rather than mechanical vibrations.

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