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IMPACT OF 3D PRINTER VIBRATION REDUCTION ON THE QUALITY OF ITS PRINTOUT

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Abstract: The authors focused on the study of vibrations of the 3D printer structure caused by the movement of the extruder during the FDM additive manufacturing process. On the basis of the tests, vibrations were passively reduced to improve the dimensions (resolution) of the final products. The vibrations were minimized by modification of the printer structure and the use of additional energy dissipation elements. Correctness of the actions taken was verified by the measuring system. After the modifications, the same series of measurements as in the initial structure were carried out to observe the changes that took place under their influence. On the basis of the tests carried out, the positive effect of reducing the vibration amplitude of the structure by about 50-70 percent was confirmed, which significantly contributed to the improvement of the final product's dimensional parameters.

Key words: 3D printing, reduction of vibrations, 3D printer design, FDM additive manufacturing process, modification of the printer structure.

1. INTRODUCTION

More and more often 3D printers are used in our everyday and professional life [1]. This method of printing has been improved significantly in recent years. As manufacturers launch new printers, their end products become more durable components, which are made of materials such as titanium. 3D printers have become popular, and due to the low cost of manufacturing and simplicity of use, many people are able to build such equipment individually [2]. Printing on 3D printers can partially support (or sometimes replace) conventional machines such as a lathe, milling machine or grinder [3]. In the current period of the coronavirus pandemic, 3D printers have proven themselves as manufacturing devices, used for example, in manufacturing of face shields or respirator components. Duration of the process while maintaining its high quality was one of the problems that appeared during the printing of components [4,5].

3D printing is a state-of-the-art process during which components of any shape and application can be manufactured. The wide range of 3D printing technologies and materials used for printing cause 3D printers to have more and more applications in various industries, medicine, architecture, etc. [1,6]. This article presents methods for reducing mechanical vibrations of a 3D printer with FDM (Fused Deposition Modelling) technology. Vibration reduction has a significant impact on the quality of the product that we get as a result of printing. The printing method is based on laying the fibers layer by layer on a build platform. The fiber is partially melted and extruded through a heated die [7]. FDM is one of the most widely used and fastest growing methods of 3D printing in additive manufacturing technology. Despite many advantages such as wide range, material availability, low maintenance and operating costs [8], the FDM method also has limitations related to the quality of geometric parameters (dimensions) of the final products [4,9]. The impact on the parameters is closely related to the resolution of the parts manufactured during the AM (Additive Manufacturing) process by the FDM method. Factors that have a direct impact on product's resolution include process parameters, product design, and material properties. Analysis of 3D printer's vibration in various studies concerned mainly the quantitative determination of the impact of printing parameters on the structural features of printed products [10,11]. In the papers [12] the impact of vibrations on the mechanical properties of printed parts was tested. The authors of the work do not deal with vibration tests of finished products, but with the study of the impact of changing the structure of the printing system on the quality of printing parameters. The authors focused on examining the vibrations of the printer structure during the FDM printing process. Based on the tests carried out, passive vibration reduction (dampers) and design changes were used to improve the dimensional parameters (resolution) of the final products. This new approach to the problem improves the effects of printing on 3D printers. The authors were testing one type of a printer obtained the results that can be successfully applied in other printers. Specifying the procedure for reduction of structural vibrations that affect the quality of printed products were the tests objective. The methods for reducing the vibration indicated in the paper such as changing the structure, applying vibroisolation are generally available to every 3D printer user. It has been shown that it is possible to change the quality of the printout by using solutions available and possible to be implemented by every user of 3D printers. In addition, tests show that vibration reduction of 3D printers should be introduced before starting any research work to improve print quality. The paper did not analyses the modal [13-16] printer before the introduction and after the application of the proposed solutions. Because such an approach would apply to only one printer model, and the intention of the authors was to indicate an experimental method of reducing vibrations of 3D printers (different models) in order to improve the quality of printed objects. Reducing the vibration of the printer affects the quality of the final product, in particular the accuracy of the surface finish.

2. MATERIALS AND METHODS

The wide range of 3D printers manufacturing capabilities and the simplicity of their operation mean that the number of companies that are equipped with this technology is growing. Among individuals, 3D printers have also become popular, and due to their low construction costs and ease of use. Final volume of the detail is the main limitation of additive methods, the working areas are limited, which often determines the need to divide the manufactured element into sections and assemble it. Various materials are used in manufacturing the components. Their selection depends primarily on the requirements for the final product. In the considered additive manufacturing method, there are materials of different characteristics. There are flexible, wood-like, hard, brittle and many other materials, but the operational parameters of the device are selected individually. The temperature of the extruder, the temperature of the built platform, and in the case of some materials also the need to use a heating chamber are the most important differences between the individual components [17, 18].

Depending on the solutions used, each machine can be tested for optimization in various respects. In the case of minimizing vibrations in machines, the first thing to do is to find their source. In many situations, there is more than one solution to improve the printer operation. In such a situation, you need to analyse the advantages and disadvantages of each solution, and then implement the best one [13-16, 19, 20].

Vibrations have a negative impact on 3D printing quality, so damping of these vibrations should be considered. Before starting to use a 3D printer, it should be checked whether it can be improved by applying the modifications so that the effects of its operation meet the expectations of users.

2.1. Design of the tested structure

The discussed printer has a frame structure made of acrylic components in combination with threaded rods. Acrylic components are laser cut and they fit tight. Each component is connected by a keyway and screwed with at least two M3 screws. Manufacturer did not inform about tightening torques or gluing the surfaces between the components, so all connections are tightened to the limit. The most important area of a printer is this place, where dynamic displacement occurs. Manufacturer provided installation of sliding shafts in an acrylic frame stiffened with ø10 threaded rods. Such a connection of the printer base is not precise. Once the position is set and the locknuts are tightened, the entire base structure tends to twist. As a result, adjustments must be made to bring it into alignment. Slide shafts were embedded in the acrylic components, which, if poorly aligned with the laser-cut holes, cause clearances. Each mechanical component of the printer is rigidly connected to the acrylic component. The XYZ system is used in the construction, in which the X axis is related to the movement of the extruder cart, the Y axis to the movement of the built platform, and the Z axis to the height - shown in Figure 1. In the case of the tested object (3D printer), the working area is 220 /220/240mm. To extend the working area, the entire structure must be modified and adapted.

List of components, Figure 1:

1.Structure frame – consists of acrylic components cut to size and screwed together with M3 screws and M10 threaded rods.

2.NEMA 17 SL42STH40-1684A stepper motor – it is the main driving component of the kinematic links, which converts rotary motion into sliding motion in each of the axes. The same motors were used at each place to systematise control and monitoring and additionally to facilitate the device servicing.

3.Extruder – in the used set, the extruder includes: motor, heating block, fans and filament feeding mechanism. The used filament feeder is called "direct". Motor has a mass of 280g, and during movement along the X axis, it has a great significance for the moments of inertia.

4.12V 240W power supply – is a switched-mode power supply unit that powers all printer components. Its operating parameters are responsible for interferences generated when turning on the heating of the built platform and the heater.

5.220x220mm built platform – is equipped with a resistance heater, which is controlled by software and is turned on to warm up and to maintain temperature of the platform. Heating of the platform is required for some materials due to surface adhesion. In addition, measures are used that keep the print in the right place up to a given temperature, and after its decrease, allow the print to be easily removed.

6.Flexible aluminium coupling – to reduce the difference in axial and radial displacement of the lead screw in relation to the motor’s rotor. It also allows to eliminate the stresses on the Z axis.

7.Toothed drive belt GT2 6mm – the toothed belt, together with the wheels, is responsible for changing rotary motion into progressive motion.

8.Linear bearings LM8UU – are ball bearings with a closed circuit, which enables them to move along the sliding shaft with little resistance.

9.Motherboard – it is a dedicated board provided by the manufacturer, which, by integrating each module inside, prevented users from individual modifying the drivers.

Fig. 1. 3D printer base structure built on an acrylic frame. 1- structure frame, 2- stepper motor, 3- extruder, 4- power supply, 5- platform, 6- coupling, 7- drive belt, 8- linear bearings, 9- motherboard.

The measuring system was assembled on a specially designed and printed board isolating the circuits of the systems from the metal frame structure (Figure 2), which ensured sufficient safety and electrical insulation to avoid short-circuit problems. The sensor on the carriage was installed with the help of printed adapters, which were designed to limit the possibility of free movement of the attached sensor as much as possible. The accuracy and effectiveness of the measurements depends, among other things, on the way the sensors are attached. The sensors used on the carriage (Figure 3) and table (Figure 4) were attached to fixed connections with glue, what ensured sufficient stiffness of the connection. The sensors on the frame were installed (Figure 5) in adapters that allow them to be screwed to the slots in the 3D printer profile. Arduino controllers and InvenSense MPU-6050 accelerometer modules were used to build the measuring system.

Measurements were taken before the introduced changes and after introducing the changes to one parameter. Then the differences were observed and when these were imperceptible, the next parameter from the list of selected parameters influencing the given measurement was modified. Measurements were made in three areas of the printer, as shown in Figure 9. The developed procedure consists in generating a file using the measurement system and generating acceleration characteristics in order to compare the results in a specific area. The signal from the sensor in digital form is sent to the slave controller, which acts as a transducer and generates the mapped analogue signal on the output, to enable the master controller to read it. The signal in analogue form is received by the mother controller and then scaled before saving.

Then the decoded signal as a numerical value is assigned to a variable, which in turn is saved in the data file. The variable used to save the file is updated according to the data readout, thanks to which the signals are added to the file in real time. Each parameter is saved every 12ms. After the measurement is completed, it is necessary to properly process the results. For this purpose, any software that can generate graphs based on data can be used. In this project, it was decided to use the Scilab software, which enables the acquisition of a sufficient amount of data and selection of a preview of the characteristics in the measuring time unit.

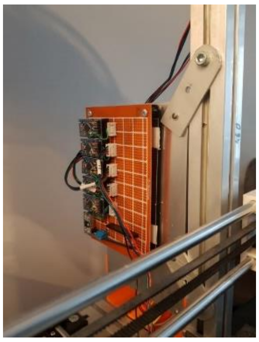
Fig. 2. Measuring system installed on the 3D printer frame

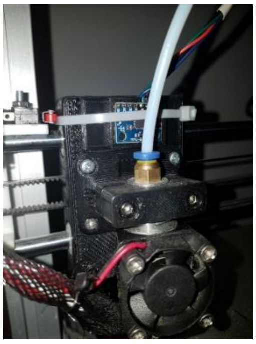
Fig. 3. Sensor installed on the carriage, measurements of acceleration in X axis

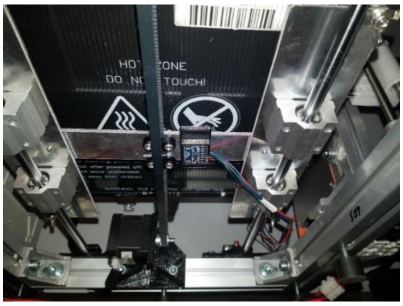
Fig. 4. Sensor installed on the worktable, measurements of acceleration in Y axis.

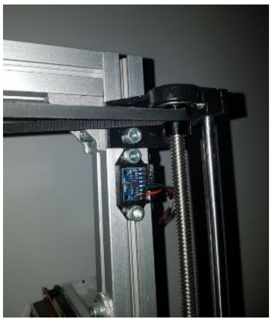
Fig. 5. Sensor for measurements in X axis installed on the frame.

2.2. Reduction of vibrations by design modifications

The movements of the device's trolley can be freely configured depending on the layer height, expected quality or strength of the final printout, therefore the type of material from which it is made was not taken into account due to its insignificance in the conditions of mechanical vibrations.

2.2.1. Change in driving belts tension

In the discussed design (before the changes) were used toothed belts of width 6 mm and a tooth pitch of 2 mm. Such a belt is light, flexible and durable, what makes this type of solution very popular. Polyurethane is the material used by the manufacturer to make belts. This is an elastic material but has low tensile strength. The belt is made of a uniform material, which makes it very flexible but does not have a high tensile strength. To improve the operational parameters of this type of strips, manufacturers use a solution with encapsulation of steel or glass fibres inside the material. Such a solution causes that the belt does not lose its elastic properties, which are required to move on the toothed wheels, and gains resistance to tensile forces. Another aspect of using the toothed belt is its automatic elongation under the impact of temperature, operation and wear. Special tensioners are installed to correct the differences generated by the decrease in the accuracy of the belt tension, which, depending on the requirements, are manual or they automatically tension the belt to the required stiffness. In the printer design, the manufacturer used a solution limited to using the homogeneous belt without reinforcements and without using any method of changing the belt tension.

To eliminate vibrations caused by the belt, the toothed belt was replaced and reinforced with steel fibres, and a manual tensioner with tension adjustment was installed.

2.2.2. Ball bearing replacement

The main parameters of the bearing are its type, diameter and thickness. When the bearing is to be used in professional machines, additional parameters are also taken into account, such as: the type of material used, accuracy, critical speeds or possible force transmission [21, 22]. In the case of the considered design for bearing guidance, the manufacturer decided to use hardened bars in combination with linear ball bearings. By moving the carriage and the built platform along their axis of advance, vibrations generated by the inaccuracy of the rolling components of the bearings are felt. There are several solutions to this problem. One possible solution is to buy bearings of higher quality from another manufacturer and replace them, but this option is not profitable. The second option is to change the method of feed to roller carriages, where wheels rolling in v-slot profiles are used, transferring less vibrations due to use of rubber rollers. There are many possible modifications, but these are the most frequently used due to their cost. Another method is to replace linear ball bearings with linear plain bearings.

In this case, Ignus DryLin bearings made of Iglidur J4 material (Figure 6), which do not require external lubricants were used. The bearing was selected regarding its availability and price. The bearings are made in the form of one block, so no additional components come into contact with the guide and do not generate additional vibrations [21,22].

The ball bearings were replaced with plain bearings and the guide was cleaned before the objects were mounted on new bearings. The expected results are the improvement of the linearity characteristics of the friction forces during the sliding motion as well as the reduction of the noise generated by the rolling balls.

Fig. 6. IGUS linear bearings [23].

Fig. 7. Authors' design of aluminium frame of 3D printer.

2.2.3. Change in the frame stiffness

Frame is the main components of the discussed design of the device. The way in which each component is seated inside the structure affects the forces and torques. Usually, manufacturers carry out a series of tests before the final design, but often there is a need to modify the components of the assembly and changing the basic structure. Sometimes it is enough just to strengthen the existing frame. If this is not possible or it is not expensive to produce a new frame, this solution is chosen. In the case of cheap solutions (often in the case of inexpensive printers for home use) offered by the discussed printer manufacturer, the stiffness of acrylic components is sufficient, when printing speeds do not exceed 40mm/s. Above the aforementioned speed, noticeable movements of the structure are visible, which allows concluding that the frame stiffness is too low. There are ready-made solutions for stiffening the structures, but it was decided to build a new structure based on 30mm x 30mm aluminium profiles (Figure 7). Availability of the material and its price decided about the selection of material for the frame. Such a structure, reinforced with appropriate angle members, is sufficiently stiff to ensure the possibility of using higher printing speeds.

2.2.4. Using the vibration dampers

The use of shock absorbers in the structure is one of the passive methods of preventing the system from vibrating. The use of vibration isolators, consisting in placing a machine or device in a specific way on the foundation, is one of the most common methods of damping device vibrations. In a situation, where the machines do not need to be fixed permanently, efforts are made to isolate them from the environment, so that they cannot be affected by any external conditions. Rubber components with high internal friction are often used. The elasticity of rubber and its properties depend on the production process and the material from which it is made. Rubber components are often subjected to compression, stretching, shearing or twisting. Appropriate selection of the material and its characteristics in the planned environment determine its use [19].

Vibration damping elements were used in X and Y axes of the driving motors, Figure 8a. However, in order to isolate the structure from the surface, the rubber base vibration dampers were mounted to the frame base, Figure 8b.

(a) (b)

Fig. 8. a) The damper of a motor twisting vibrations b) the base vibration damper [24].

2.3. Reduction of mechanical vibrations by changing the parameters related to movement

Vibrations generated in machines are not always the result of clearances or inaccuracy in manufacture and assembly of each component. They are often caused by the operation of other components, e.g. actuators. The double-acting pneumatic cylinder has two positions depending on the setting of the pneumatic valve, which, after switching the coil, gives the maximum pressure on the piston rod. As a result, the piston rod tapping to the end of its range of movement hits the limiter, causing oscillations. Mechanical pressure dampers can be used to reduce this effect but they have a disadvantage in that they restrict flow throughout the valve's actuation period. In order to optimize such a system, the control system and the actuator should be adapted so that in the feedback loop, the controller "knows" when a given damper is to be activated and with what power. These are not common applications, as when you decide to install an actuating unit, you can predict the operation of each component and immediately apply programmable and individualized industrial solutions.

3. RESULTS

3.1. Measurements of mechanical vibrations before and after modifications

Reducing the undesirable mechanical vibrations in the considered structure was the tests objective. Measurements were carried out systematically, both before and after the introduced changes. An important parameter affecting vibrations is temperature. Printing before and after the changes was carried out under the same ambient conditions. The tested printer is intended for home use, therefore the printing took place at room temperature. Measurements were taken in three areas of the printer as shown in Figure 9. Due to the readability of the results, after collecting the data, the worst-case scenario was selected and used as a test one. Several measurements with smaller amplitudes would generate too much data for analysis, which in consequence could cause large delays in re-measurements and difficulties in generating characteristics. The developed procedure is based on generating a file using a measuring system and vibration characteristics to compare the optimization effects in a defined area.

The measurement is taken by simultaneous switching on the measuring system and running the defined program in the 3D printer. Then, according to the g-code, the printer travels to the measurement site, and then starts fast movements with a speed of 100 mm/s and an acceleration of 3000 mm/s^2. The programmed speed is only theoretical, due to the distance between the measuring sections, and cannot be reached. After completion of the test run for the first area, the printer makes another travel waiting two seconds before making the next series of test movement. When the test travels are completed, data from the memory card is downloaded and processed to generate graphs showing the resulting movement characteristics. According to the assumptions, on the basis of the obtained graphs, a shorter test program is generated for the places most susceptible to vibrations, where the speed of movement is limited by the software to 50 mm/s.

Due to no need to calibrate the measuring devices, the number of measurements is limited only by the ability of the program to process data. However, for the purpose of a standardized analysis, it was decided to compare the sections of the characteristics graphs, in which the test program reached a given speed and realized a series of movements. Such approach to the analysis increases the repeatability of the results, which reduces the analysis error.

The final measurement results of design changes were considered as input measurements for optimizing the 3D printer software. Introducing changes to the software requires changing the structure of the printer's software, and then uploading them through a special procedure. Unfortunately, such action is time-consuming, which determines the separate analysis of changes.

A test program allowing to test the acceleration in specific axes was prepared for the tests and interpretation of the results. It was assumed that the greatest vibrations are generated during rapid changes in the directions of movement, therefore the test program consists of sliding movements in the X and Y axes in which the sequences of movements were so as to generate the greatest possible overloads (acceleration). The programs are designed to excite the largest possible oscillations in the defined printer work areas (Figure 9).

Test program includes the extruder movements in the X axis in three ranges of the working area, from 10mm to 30mm, from 100mm to 120mm and from 190mm to 210mm, with the worktable set at 100mm and with the assumed speed of 50mm/s and 100mm/s. For the Y axis, the same control methodology was used in the test program.

3.1.1. Measurement of the frame vibrations in two points

The first two vibration measurements were taken on an acrylic frame and an aluminium frame without any additional vibration dampers. For this purpose, measuring sensors were installed in the upper corner of the structure in the same orientation for both structures. In order to intensify the effects and increase the values of the measured parameters, it was decided that the printer carriage would work in the upper position at a height of 150 mm. This height was selected as with prints heights, the prints quality decreases proportionally to the size.

Acceleration characteristics of the acrylic frame sensor similar to acceleration in the carriage of the aluminium frame (Figure 10) shows a strong impact of the motion forced by the motor on the structure vibrations. These movements depend on the direction in which the carriage is moving. The measurement was taken when the frequency of movements stabilized, so that it was possible to observe the key elements of the process. According to the marked peaks of the measured amounts, a significant improvement and smoothing of overloads time process can be noticed.

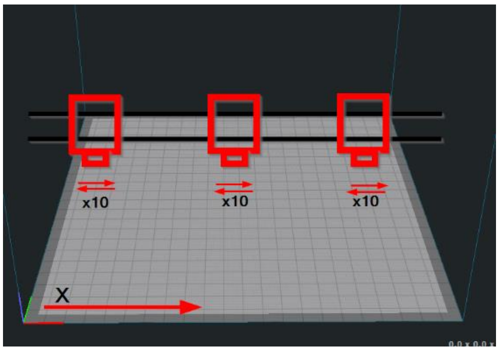

Fig. 9. Graphical presentation of the given test movements of the carriage in X axis.

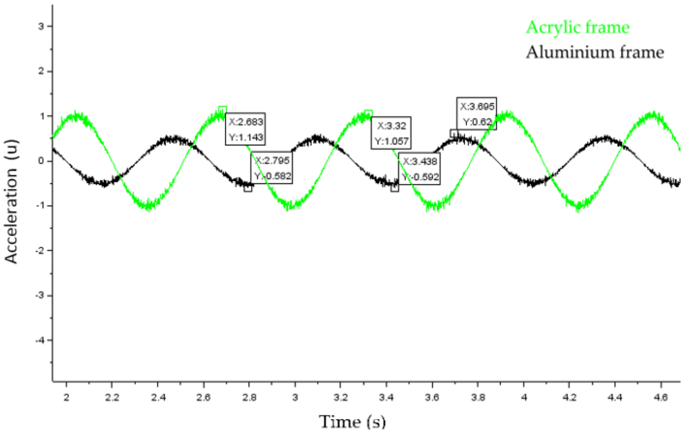

Fig. 10. Measurements of acceleration in the selected area of the structure (1u = 490.5 mm/s^2).

The maximum overload in the tested area was: 518.46mm/s^2. However, after rebuilding the frame, the acceleration generated by the carriage movement visibly decreased, which enabled reducing the overloads to 304.11mm/s^2. Based on the measurements, it turns out that the change in the frame design resulted in a significant improvement regarding the vibrations. The overloads decreased by 225.63mm/s^2, which is practically half of the original maximum value of the measured quantity. Due to taking the measurement in the top position of the carriage on the Z axis, it was not necessary to take measurements using the built platform.

Installation of dampers was the next stage of the structure modification. According to the assumptions were used the dampers in the form of additional legs as an insulation between the ground and the structure. To observe the changes, after equipping the device with the vibration dampers, subsequent measurements were made and compared.

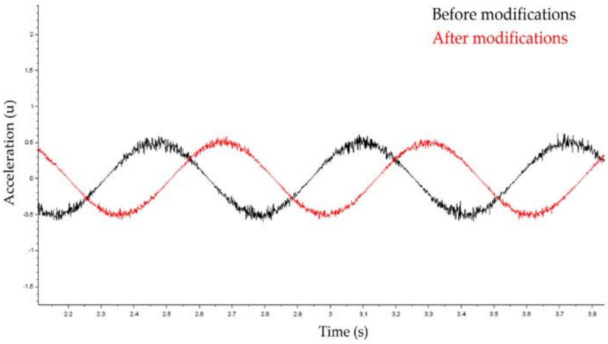

Fig. 11. Diagram of dampers impact on the vibration characteristics (1u = 490.5 mm/s^2).

Installation of damping elements in the 3D printer structure appeared to be an effective solution in terms of vibration damping. The measurements show, however, that it has a negligible effect on the structure components, Figure 11. The measurement shows smoothing of the input signal from the sensor, which indicates the improvement and reduction of vibrations but this change is so slight that it will not affect the print quality.

During the first start-up of the device with the dampers installed, a significant decrease in noise and vibration of the table, on which the structure was standing, was observed. The expected effects, which could not be observed in terms of print quality, are translated into a positive impact on the environment.

3.1.2. Measurements of acceleration and modifications in X and Y axes

The printer carriage moving along the X axis is the most dynamic element of the entire structure. On the other hand, vibration affecting the quality of prints is only during continuous printing, when the Z axis is activated only to change the layer. For this reason, for the proper tests, the accelerometer should be placed in the appropriate direction, so that the sliding motion of the carriage is parallel to the sensor axis. The power cables and the tube feeding the material for printing are inseparable components of the carriage. These components may cause measurement disturbances but it is necessary that they should be as close to as possible the carriage. The sensor was fixed and connected by a four-wire cable to the socket in the system. The weight of the sensor in relation to the weight of the entire trolley is negligible. However, to ensure that the weight of the sensor does not actually affect the movement characteristics, the measurement was carried out over a distance of 10 mm.

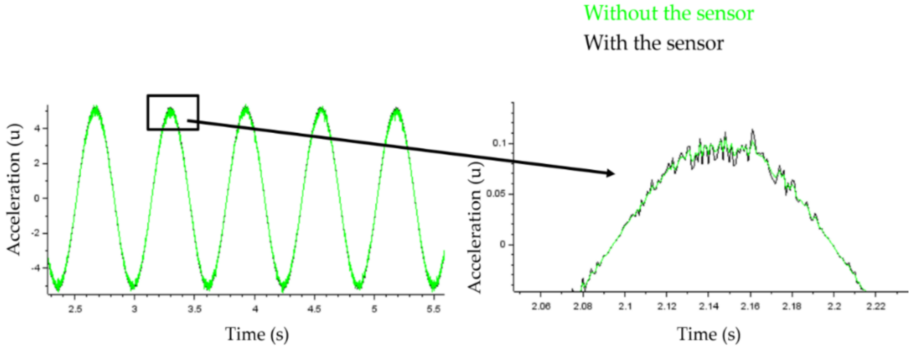

Fig. 12. Diagram of difference in acceleration with and without a sensor (1u = 490.5 mm/s^2).

In Figure 12, as a result of the comparison, you can see the minimum difference in the amplitude between the measurements, which may indicate the impact of the sensor weight on the measured value. However, the target test covered the entire structure and assuming that the sensor is on the carriage during the entire measurement. There is no need to make corrections due the extra weight and the measurements will not be distorted. After starting the first measurement and analyzing the movement characteristics, the area, where the greatest changes are visible was determined.

After taking measurements on the original and modified belt (Figure 13), a small difference in vibration parameters is noticeable.

The difference in the maximum readings between measurements is 0.1 units. This is a small difference from the total acceleration, but it has an impact on how this mechanism works. The parameters (Fig. 14) also show a very clear change in the inertia of the trolley at the point where the direction of movement changes, which is shown by two sections x_1 and x_2. When analyzing the cross-section of the drive belt, it can be concluded that it is caused by the inertia of the trolley, which, due to the elasticity of the belt without fibers, has a larger vibration amplitude. After determining the cross-sectional ratio, which was 2:1 (x_1:x_2), it is concluded that the change of the drive belt, in addition to having a positive effect on the maximum overload, also affects the element's inertia during movement.

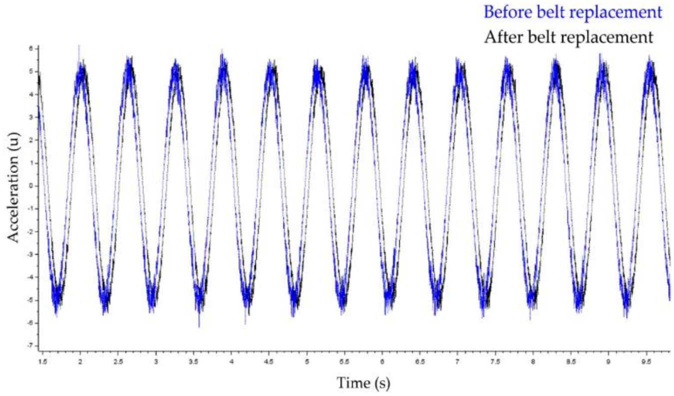

Fig. 13. Measurement of carriage accelerations before and after the belt replacement (1u = 490.5 mm/s^2).

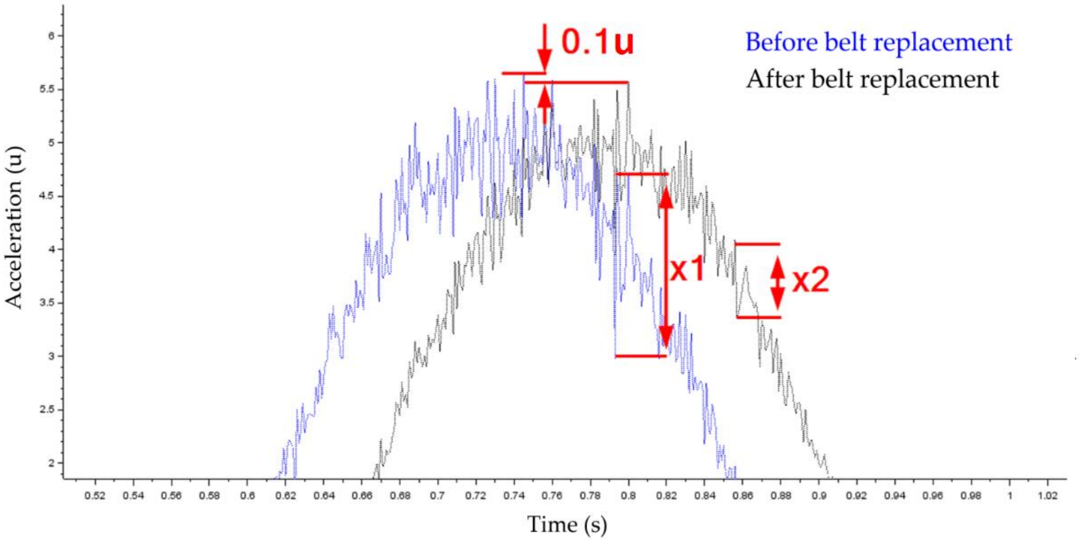

Fig. 14. Close-up of Figure 13, revealing the difference in parameters (1u = 490.5 mm/s^2).

The ball bearings were replaced to reduce vibrations in the Y and Z axes of the 3D printer carriage. After removing the belts and manually trying to move the carriage, slight jerks could be noticed caused by the jamming of the balls inside the bearing during movement, which resulted from the fact that the manufacturer used the type of base bearings. Bearings with balls in the housing cause additional noise, which also affects the use of the machine. According to the assumption, due to the difference in the operation of both types of bearings, vibrations in the Y and Z axes with the use of self-lubricating plain bearings should be practically eliminated.

After the measurement of acceleration difference, the diagram shows the difference in the operational parameters during the carriage slide over the rollers. In both graphs, for the Y axis and for the Z axis (Figures 15, 16), a significant improvement and reduction of sudden changes in the acceleration parameters can be observed. According to the measured minimum and maximum parameters, in the case of measurements that took place before and after changing lanes, the acceleration decreased by 50% for the Y axis and by 30% for the Z axis. When we consider the Y axis, a 50% reduction in acceleration may indicate that that only vibrations from the engine were transmitted to the sensor. A smaller decrease in vibration parameters for the Z axis may be due to the design of the carriage, the mass of which acts downward with the force of gravity, additionally increasing friction. According to the measurement of acceleration, it can be observed that acceleration parameters before changing the bearings are similar for both axes, while after replacing the bearings, vibrations on the Y axis were reduced significantly.

Similarly, to the vibration measurements in the Y and Z axes of the carriage, after replacing the ball bearings with plain bearings, vibration in the X and Z axes was measured by the sensor installed on the built platform. This measurement enabled clearly establishing the effect of replacing the ball bearings with self-lubricating plain bearings. Bearings in the moving parts are installed in pairs, causing the additional reduction of clearances for the carriage in the Y axis and for the built platform in the X axis (Figures 17, 18).

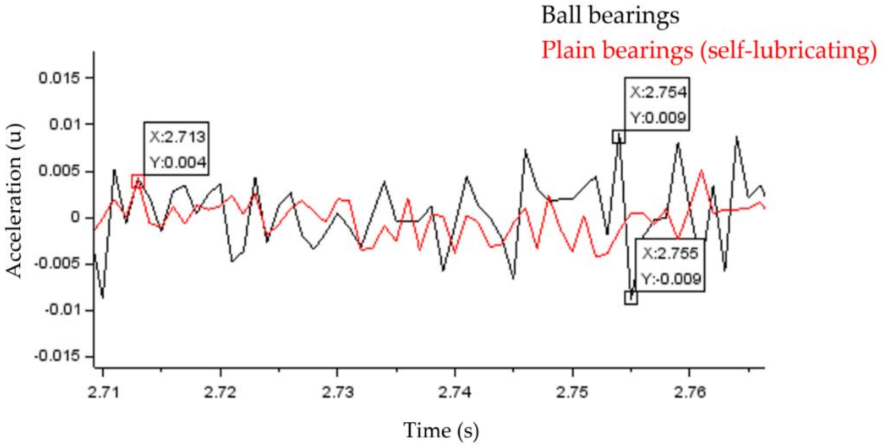

Fig. 15. Replacement of the bearings: vibrations in the Y axis (1u = 490.5 mm/s^2).

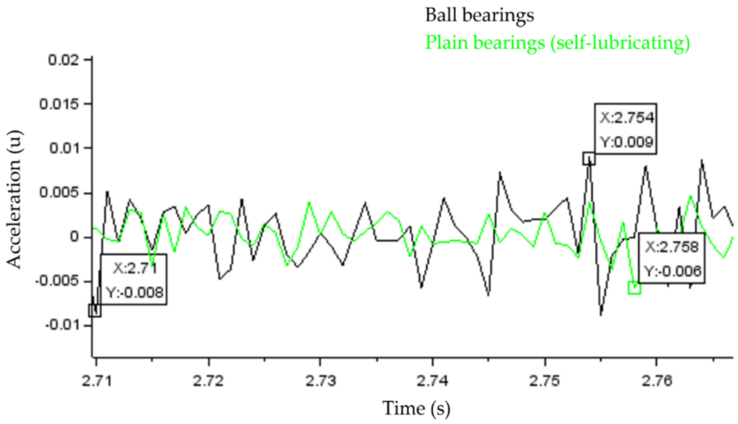

Fig. 16. Replacement of the bearings: vibrations in the Z axis (1u = 490.5 mm/s^2).

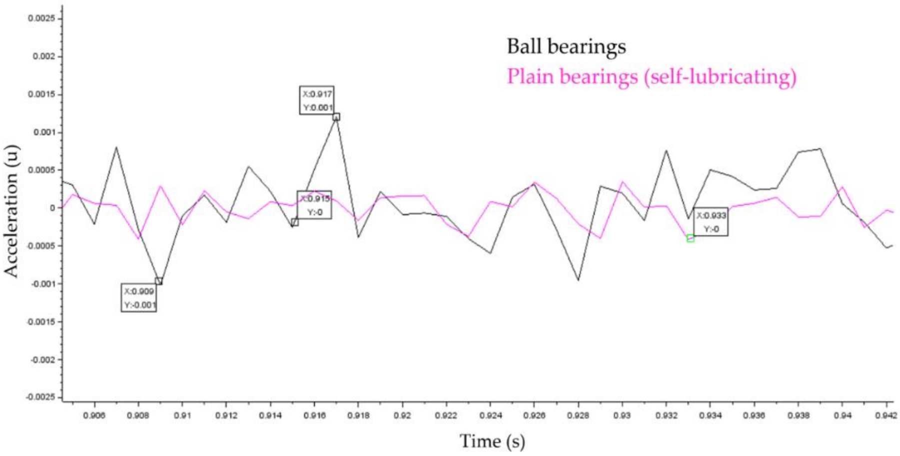

Fig. 17. Replacement of the bearings: vibrations in the X axis (1u = 490.5 mm/s^2).

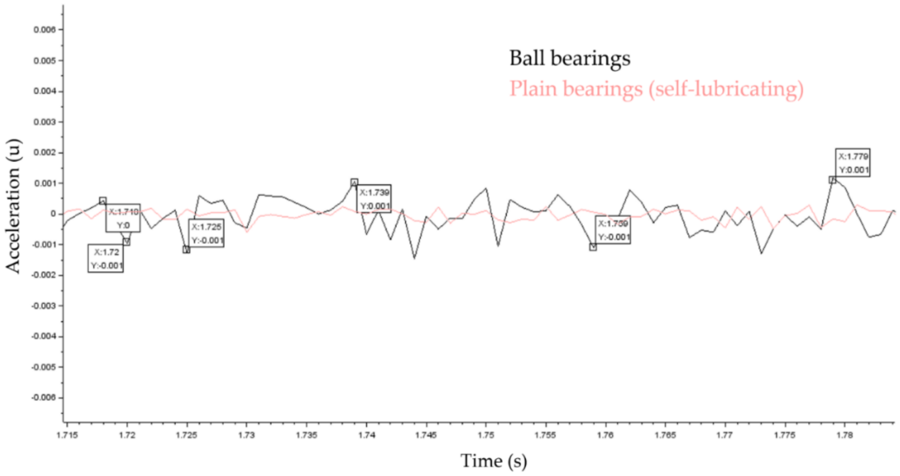

Fig. 18. Replacement of the bearings: vibrations in the Z axis (1u = 490.5 mm/s^2).

4. DISCUSSION

In the presented research work, the vibrations of the 3D printer were tested. A printer model that is widely available for "home" use was tested. The aim was to check if the vibrations affect printout quality and how to improve the end result using the generally available solutions.

Already during the first observations of the printer's operation, vibrations of the structure were noticed. Using the device in accordance with the manufacturer's recommendations, i.e. printing speeds and accelerations specified in the supplied software, displacement of the upper frame components, which was designed to support the Z-axis guides, was observed. Despite the stiffening of all joints, the vibrations were still felt. In this case, it was not

possible to produce a perfect print. Components printed at low speeds and accelerations were of good quality, but when these parameters were increased (speed, acceleration), they lost quality.
Before taking any action, a model of a test cube with dimensions of 20x20x20mm was prepared, the printout of which was a reference item to confirm justification and effectiveness of design modifications. As you can see in the comparative photo (Figure 19), it was possible to improve the print quality and keep the assumed dimensions after printing according to the model.

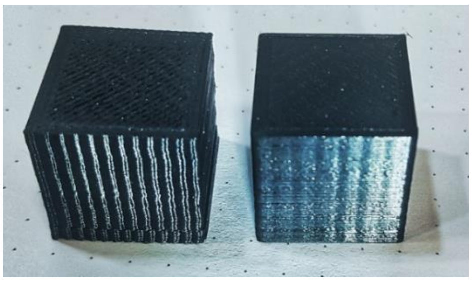

Fig. 19. Test printout. Left: before optimization, right: after optimization.

Universal measuring system that can be adapted to a different types of machine (3D printer) for similar asks is the result. The intermediate goal was to increase the quality of the printout along with shortening its time and reducing machine vibration - this goal was achieved. The tests also showed that it is necessary to measure the level of vibration of 3D printers and minimize them in order to improve the quality of the final product. Such tests should be a preliminary stage, preceding, for example, the tests to increase the dimensional accuracy of the components produced during 3D printing.

5. CONCLUSIONS

Particular attention was paid to the measurement method. Proper location of the measurement sensors was the key issue of the correct measurements. The sensors were attached in accordance with the directions of the mechanisms movements.
Due to the change of the frame of the structure, measurements before and after the frame change were compared, and subsequent measurements on the stiffened structure only were decided. This approach, assuming a decrease in the vibration amplitude in the structure, will increase the accuracy of subsequent measurements.
The changes started with the frame as the structure base, which appeared to be a key element in achieving the increased machine efficiency while reducing vibration. This was achieved through the use of a frame made of 30x30mm aluminium profiles, which, when properly screwed and stiffened, guaranteed minimal movement of the structure compared to the structure based on acrylic profiles. As a result of the above modification, the vibrations in the place most distant from the motor that activates vibrations, generated overloads lower by 0.023g. Tests were carried out on previously programmed movements and straight sections.
When using the vibro-isolators, a negligible effect of vibrations damping on the characteristics of the carriage movement was observed, may be due to position of the machine. The printer was tested on a heavy, stable table that absorbed vibrations from the surface. Despite a slight improvement in vibration damping parameters, generation of noise was then significantly improved. Vibrations in the machine are transferred to the base which emits the sounds to the surroundings.
With regard to the X and Y axes, it was decided to apply several methods to improve the smoothness of the movements of the carriage and the worktable. In both cases, before starting the measurements of introduced modification, the vibration amplitudes were measured in places depending on the distance between the moving component and the drive motor. When these places were determined, acceleration measurements were started using the drive belts supplied by the manufacturer. To observe the impact of the belt and weight of the moving component on the acceleration, the measurements were taken for both axes. Reduction in measurement jumps in the zone of changes in the rotational direction of the motor, and reduce in overloads to the moving parts by 0.004g, which is much less important than the smoothing of the acceleration signal in the system was the result of using the toothed belt with a glass fibre frame. Linear bearings were also replaced, allowing the carriage and the worktable to move. For these both components, an improvement in the smoothness of movement was achieved. Vibrations on moving parts have been reduced by 30% and 50%, which is a very good result. This was possible by removing the extra balls from the ball bearing movable joint.

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