Vibration Analysis of Cantilever shaped 3D printers

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Abstract. 3D printers are being explored by many of the industrial giants and daily customers as an excellent replacement for some of the traditional, inefficient, costly and waste producing techniques of manufacturing. Although, still at a premature state of development, and being thoroughly researched upon, there is lack of data concerning the physical strength or a proper machine design development for this 3-axis automated machine. Other, while being able to create a robust machine, over-utilize the resources. In this paper, we attempt to explore how analysis of vibration using minimal equipment could refine the quality of 3D printing as well as how would one improve the design to yield best results. The study is most relevant for the online open source community e.g. RepRap, within the development in new 3D printers design.

1. Introduction
The additive manufacturing technology has been around for about 15-10 year time. 3D printing (3DP) has taken even much more interest from hobbyist and other ‘do it yourself’ (DIY) community since the expiration of licenses relatable to the process [1]. Currently, new patents regarding the intellectual copyrights have been issued due to which, certain designs are protected against reproduction through 3DP technology [2]. Although, given the current scenario, the industry has long moved towards better and more efficient techniques for additive manufacturing. It is only recently that consumer electronics in many countries are now displaying their desktop 3DP on shelf, and also attracting many educational institutes for being able to teach students and empower them with this creative machine. Industrially, it is SLS or Multijet technology that is most frequently encountered as additive manufacturing method [3]. This technology is by far, too expensive to be able to currently replace the existing technologies used for metal manufacturing processes such as CNC and die manufacturing. Most of the general public is only introduced to FFF or FDM printers. Even the current scientific community rely highly on the said 3D printers to create equipment for use. It is now a basic commodity, which could be easily noticed within all research laboratories. With various firmware available online as open-source, many people often choose to build themselves a 3DP. Much of parts are relatively easy to obtain from online market, with majority also selling DIY kits [4].

1.1. Emphasis on Mechanical Properties
Even with all the spreading awareness about the technology, much of the intrinsic mechanical properties of FFF 3DP and its terminology is undergoing rapid changes. Most of the researches currently focus on different kinds of experiments being performed on the products of FFF 3DP. Two similar CAD files processed using FFF on same machine, could differ significantly with variations in raster angle, extrusion temperature, infill amount and the speed of printing. Many other factors might be in action, but the ones which could be easily measure and controlled quantitatively, often end up becoming the topic of research [5]. These data are extremely important in having to provide engineers general values
that they could embed in their designs directly. There has been a growing report on engineers developing automobile parts, as well as whole cars out of FFF 3D printing, which without say, would have involved multiple design factors related to the material and the final product being used for fabrication [6]. With the intent of contributing to this ever-increasing database and proposing more scientifically rich information, this paper shines lights on one of the few aspects of the process which have a major effect on the mechanical and surface properties of the printed products.

1.2. Vibration and Design
The expectation of general consumer before using 3DP is comparable to the quality obtained from die manufacturing of plastic, but as one realizes it differs remarkably due to layers visible from processing. These layers are small and could be neglected as one gets used. The problem arises when vibration of machines persists to distort the surface quality, of the final print. Although, many post processing methods have been developed to change the outlook of the final product in variety of ways, these layers give many users a good deterministic factor of the quality of 3DP. As a thumb rule, when the layers are big, irregular & wavy, the final product diverts from delivering the best quality. When the layers are hardly visible, or the texture of the final product, such as curves or depressions, are clear, the final product is good quality, even though some of the layers would still be visible.

2. Machine Design of 3D printers
Due to the growing numbers of people utilizing FFF technology, there are a number of categorization in articles, based on different features such as the geometric system, type of extrusion, basic mechanical structure and production capacity [7] [8]. Though here, we utilize yet another classification to suit the flow of our experiment and make it easier to understand. Most customer chose to opt for using either an open type 3d printer or using a closed 3D printer, more commonly known as moving bed and fixed bed design, respectively. This is because in an enclosed 3D printer, the bed usually comprises of z-axis movement (5% of TPT), which moves only up and down with succession of each layer, and remains stationary for planer movements. The open printers on the other hand, usually have a bed which forms either the x-axis or the y-axis (95% of TPT).

2.1. Fixed Bed and Moving Bed
The fixed bed printer, also called enclosed printers are covered using metal, fibre composite or other stiff material able to withstand the torque produced by the motor travelling throughout the whole mechanical assembly. The downfall with these types of printers is that they are relatively expensive owing to the cover material required. There is also a requirement of a complex mechanism for the movement of the planer axis, which in turn necessitates the use of large number of bearings, guide rods and toothed pulleys also Fig 1 (a).

The moving bed printers are the most common printers that are popular among DIY electronics. They are cheap, sturdy and reliable. Most of these printers are operated by hobbyist and DIY community. They are used to explore more options and customization that could be performed to be able to improve the quality of the print. It could be easily made using a variety of mechanism to move the extruder Fig 1 (b). Some examples include polar movement, delta mechanism and hanging 3d printer [9]. The major problem with these printer is vibrations, and that too owing to the bed. Since the bed is the heaviest element, its movement is bound to source some vibrations which cause different kinds of defects [10] [11].
2.2. 3D Printer for Experimentation

We could intuitively prove that vibrations are inherent problem. It could be further multiplied as the material keeps on depositing on the build plate, but no such formal study has been attempted over the subject. It remains the aim for the rest of the discussion to investigate and interpret the results of vibrational analysis of moving bed 3D printers.

Due to many reviews and complications faced by existing users, it was decided that the machine to be analyzed would be developed from very start to the point of perfection. A brief research at existing study indicated that some experimentation has already been performed on the fixed bed 3D printer [12]. The analysis performed utilized the vertically recorded displacement using a laser sensor, to infer the quantitative measurement of vibration, although such approach is seldom observed in the vibrational analysis [13]. Furthermore, the vibrational displacement was measured for the bed axis only. As we have previously stated, the vibrations should be measured for axis which moves frequently and also carries the largest weight. The axis which satisfies both the stated condition is the planer axis. Thus, the vibrations in the fixed bed 3D printer should be measured relative to the extruder, not the build plate. The study here aims to analogically provide the missing link about the vibrational analysis of moving bed 3D printers.

2.3. Development of 3D printer for Experimentation

Since our team were settled onto designing the whole machine themselves, they had to liberty to explore as many alternatives as possible which could optimize the performance and reduce the cost as well. Most moving bed 3D printer are available in two different types. The first one is also called square frame, while the other one is known as cantilever structure (C-shape). Most of the available printers fall into the former category. In an attempt to replicate the design, the CAD model in Fig 2 was developed and soon realized since most of the raw material was easily obtainable from either online stores or local hardware shops. It should be noted that the suggested design was quite similar to the currently available square frame 3DP priced under USD$250. Since the experimentation is closely connected with the user experience affordability, a design very similar to the commonly available 3DP was opted [14].

The design suffered from large vibrational currents travelling throughout the structure of the printer. There were two main problems that were encountered. Firstly, the constraints provided to the motion of the printer were not enough to provide a fully constraint motion. This was due to the part that guide rods were long enough to go through bending, and the material used for making the fixture, holding the guide rod, was flexible.

Many other problems surfaced as the use of the machine was increased. Due to lack of repeatability, and poor surface quality, the printer was labelled as prototype and a new, better and improved moving bed design was proposed, using minimal number of parts. This new design was cantilever structure as shown in Fig 3.

![Fig. 1. (a) Fixed Bed, (left), (b) Moving Bed (right)](image-url)
This design also consisted of the same number of constraint as the previous design, but the size of bed as well as the guide rod was smaller. Through the course of the development of this 3D printer, the bed was additionally constraint using a rolling wheel mechanism also.

The targeted problem for having to provide additional constraints was based on qualitative judgement of the printed object. Due to poor bearing quality, the perpendicular movement of the base was not completely constraint. Wavy layer patterns were visible, instead of the expected straight lines. Additionally, as the PLA deposited over the plate, the weight of the bed kept increasing and thus the inertia. With more inertia, the base vibrated with an increasing amplitude, even though quite subtle to be observed with naked eyes, but its effects, were nonetheless visible on the surface of the print. With the addition of another constraint, almost all the vibrations due to design imperfections were largely eliminated.

**Fig. 2.** Development of prototype showing CAD model (left) and realized design (right)

**Fig. 3.** Development of C-shape prototype showing CAD model (left) and realized design (right)
3. Experimentation

3.1. Assumptions and Procedure

One of the key for vibrational analysis is the location of the sensor. The source of the mechanical vibration could be due to multiple imperfections, few of which are systematic in nature. The sinks, although, are few and predictable. The vibration travels throughout the solid mechanical structure, similar to a wave or current. These vibrational currents end where the mechanical links are open (farthest away from supports), thus, the base and extruder form the ideal places for observing these currents physically. Due to the convenience of performing the experiment, the base was chosen as the ideal site for placing the accelerometer. The acceleration was adjusted to a default value of 800mm/s and the speed of travel was adjusted to 3600mm/min or 60mm/s. The value was further increased to 150% and then to 200%. The accelerometer recorded the variation in acceleration, and increase in speed. The data was further studied more elaborately to display the increase of vibrations in terms of amplitude and frequency.

3.2. Vibration Analysis

The produced vibrations are forced vibrations. The torque applied by the motor, which would ideally be unidirectional, is acting through all the other axis due to imperfections and tolerances of guide rods, pulley, timing belt and bearing allowances, giving rise to a resultant force acting perpendicular to the face of the bed. The vibrational analysis is performed using a MyRIO built-in accelerometer with 12-bit minimum resolution. The data is recorded at a sampling frequency 1000Hz for a duration of about 7-8s. The obtained data is further processed using FFT in MATLAB to yield more meaningful characteristics about the increase of vibration frequency and amplitude.

![Graph of vibration analysis](image)
Certain traits about the spectrum were predictable. Few peaks were expected to reoccur in spectrum, regardless of the variation in the speed. Intuitively, the frequency of the vibrations as well as the amplitude were bound to increase, simultaneously, as the speed was increased. The acceleration time graph would also contain two large peaks, which is due to the jerk produced on the bed beginning its course of movement and alternatively, completing it.

The G-code which is used to promote the motion of bed varies from firmware to firmware. In this case, Marlin [15] has $G00 \ X<units>$ as the command. The command is entered in the prompt window of an interface software called PronterFace [16].

**Fig. 4.** Time Domain Observations with varying speed (a), (b) and (c)

**Fig. 5.** Frequency Domain Observations (FFT) with superimposition of varying speed
3.3. Observations
The time domain graph did not present much information other than showing the increase in the amplitude of acceleration as the speed increases. The variance of acceleration increase by an average of about 50%. The amplitude characteristically increases in the middle spectrum, when the bed crosses the center of the x-axis. This phenomenon is clearly visible in spectrum for 120mm/s. The graphs indicate that the amplitude of the overall spectrum increases, but maximum peak to peak value is not a good comparable measurement [12]. For being able to analyze the data in a more comprehensive manner, the Fourier transform of each set of data is superimposed on the top of other. The transform revealed some of the peaks which were fixed, regardless of the variation in speed.

The FFT dictates that the higher speed result in harmonics with larger frequency. These harmonics also occur with high amplitudes e.g. Centre 1. As stated previously, certain harmonics reoccur at same point, forming a spectrum around 60Hz. Another spectrum is also formed by the collaboration of harmonics occurring in 90mm/s and 120mm/s speed spectrum.

4. Conclusion

4.1. Interpretation of Data
Most of the frequency that are caused due to vibrations, should intuitively increase with speed. A similar study carried out by a start-up in Poland supports this claim from their vibrational analysis using a laser displacement sensor [12]. An attempt was carried out, for being able to compare the obtained data with the readings of the study, but due to a low sample rate, the double integration yielded trivial values. Yet another close observation also revealed that not only the amplitude of certain frequency increases, but their frequency also increases.

The kinematics operation used by the 3D printer follows a GBRL standard, which is established by an online community. When following a straight linear path, the kinematics is very close to linear, following the three equations of motion.

As previously stated, the motion is under an influence of force, produced by the torque of the stepper motor. When the speed of the operations is increased, the motor accelerates with a higher magnitude and for a longer elapse of time. During this time, the overall torque experienced by the system and axis increases. This increase causes many of the dormant harmonics within the spectrum to become dominant.

Fig. 6. Final Quality (left) and Initial Quality(right)

Reducing the vibration in a 3DP could largely decrease the post-processing cost, and make the technology more attractive and comparable to the other polymer manufacturing techniques. Moreover, a deep study of acceleration with variation in different parameters such as the accumulated mass over the build plate, the PID constant values and different printer acceleration is also missing, which if performed, could enable users a general guide of mechanical weaknesses and strength for machine
designing using 3DP. Although larger organization may possess such data, but due to the recent introduction to this technology, the general open source community and scientific researchers who want to utilize 3DP for making their equipment lags behind.

Forming a strict analytical model out of the given data is near impossible. The system presents itself as stochastic, rather than deterministic, with a plethora of variables being neglected out of the sight of measurement. Although, there is a large scope of application of machine learning since almost no firmware supports a feedback to assist the kinematics of the 3d Printer. Almost all the firmware relies heavily on the fact that stepper motor work just fine with open loop control. Although the stated fact holds true for a large number of mechanisms, there are exceptions. These exceptions culminate themselves into inaccuracies when there is transmission of relatively large forces and torques through the motors.

This analysis was performed only after the 3DP was perfected. Although, there lies an immense scope towards the development of the machine, many improvements have already been achieved with the base of the cantilever 3DP. Fig 6 also shows how the quality of the product drastically improved. This was achieved by measuring the vibration at each advancement of the machine designing process and thereby printing the product through it. A large database of vibrational data regarding the 3DP could potentially be used to tune a 3D printer for optimum quality similar to a guitar tuner, which also utilizes frequency analysis. Furthermore, an embedded sensor could also be used to enable artificial intelligence in 3DP. The sensor may detect the vibrations, or the curves which would cause abnormally high vibrations, and adjust the G-code online to produce a better quality without using much resources. The box structure suffers from vibration for one simple reason. Since the whole assembly is directly, or indirectly joined to a host cover, the vibrational currents travel throughout, and end up near extruder nozzle which may cause small, but defects nonetheless.

4.2. Future of 3D printing
3DP is the most powerful tool for open scientific minds, to date. It enables users to access a small manufacturing plant in a highly compact way, thus enabling many of the creative individuals to access the power of rapid prototyping. There has been an increasing input from people around the world, utilizing the machine in un-imaginable ways. Many of the designs concern scientific and engineering investigation, submitted by non-technical people, thus further promoting the growing attention towards technology. In future, the manufacturing industry would not completely circle around additive manufacturing technique, as stated by our hyped social media, but tuned towards having to embed it into its larger established matrix, and, most probably, a hybrid technique of subtractive and additive manufacturing would come forth. Although such events would take place only when the price of industrial additive manufacturing falls below what is called ‘affordable’ by the manufacturing industry.

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5. References

[1] E. P. Search, "3d printing process patent," [Online]. Available: https://worldwide.espacenet.com/publicationDetails/inpadocPatentFamily?CC=US&NR=5900207A&KC=A&FT=D&ND=6&date=19990504&DB=EP&locale=en_EP.

[2] K. Walker, "The intellectual property challenges from 3D printing," Computer Weekly, September 2014. [Online]. Available: https://www.computerweekly.com/opinion/The-intellectual-property-challenges-from-3D-printinghttps://www.computerweekly.com/opinion/The-intellectual-property-challenges-from-3D-printing.
[3] S. A. & A. Peermohamed, "The future is 3D: India witnesses spurt in additive manufacturing," Business Standard, 8 August 2018. [Online]. Available: https://www.business-standard.com/article/companies/the-future-is-3d-india-witnesses-spurt-in-additive-manufacturing-118080801301_1.html. [Accessed 2018].

[4] M. Jones, "3D Printer Firmware – Which to Choose and How to Change It?," ALL3DP, 4 April 2018. [Online]. Available: https://all3dp.com/2/3d-printer-firmware-which-to-choose-and-how-to-change-it/. [Accessed 2018].

[5] K. P. B. H. Francois Decuir, "Mechanical Strength of 3-D Printed Filaments," CPS, 2016.

[6] J. Pyper, "World's First Three-Dimensional Printed Car Made in Chicago," Scientific American, 12 September 2014. [Online]. Available: https://www.scientificamerican.com/article/world-s-first-three-dimensional-printed-car-made-in-chicago/. [Accessed 2018].

[7] C. Hemlock, "Chris's 3D printing project," Wordpress, [Online]. Available: https://chayesthakore.wordpress.com/about/. [Accessed 2018].

[8] "Direct Drive vs Bowden Extruder Guide and Calibration Tips," pinshape Blog, 07 July 2016. [Online]. Available: https://pinshape.com/blog/direct-drive-vs-bowden-extruder-guide/. [Accessed 2018].

[9] K. Stevenson, "The Hangprinter: A Frameless 3D Printer," Fabbaloo, 17 March 2017. [Online]. [Accessed 2018].

[10] D. Quintans, "Diagnosing and fixing ringing versus vibration artefacts," Desi Quintans.com, 30 September 2017. [Online]. Available: http://www.desiquintans.com/ringing.

[11] Tech2e, "THIS IS Y," 13 May 2017. [Online]. Available: https://www.youtube.com/watch?v=AKTvykTPfQw. [Accessed 2018].

[12] J. D. Zbigniew Pilch, "The impact of vibration of the 3D printer table on the quality of print," IEEE, 2015.

[13] M. S. L. C. F. Al-Badour, "Vibration analysis of rotating machinery using time-frequency analysis and wavelet techniques," Mechanical System and Signal Processing, pp. 2083-2101, 2011.

[14] T. Koslow, "Anet A8 Review – Most Popular 3D Printer of Fall 2018," ALL3DP, 9 September 2018. [Online]. Available: https://all3dp.com/1/anet-a8-3d-printer-review-diyc/. [Accessed 2018].

[15] "Marlin," [Online]. Available: http://marlinfw.org/.

[16] "PronterFace," Print Run, [Online]. Available: http://www.pronterface.com/.