Solid Freeform Fabrication 2021: Proceedings of the 32nd Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

VIBRATION-ACTUATED POWDER DISPENSING FOR DIRECTED ENERGY DEPOSITION SYSTEMS

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Abstract

Users of powder-fed directed energy deposition system often face several challenges associated with conventional powder delivery sub-systems. In addition to the high cost of wasted powder, it can be difficult to plan for the amount of material being deposited when some of the dispensed powder is not captured in the melt pool. This work studies the effectiveness of a vibration-actuated powder dispensing system using a nozzle with a small capillary opening. The opening is sized so that particle contact forces arrest powder flow when the vibration actuator is turned off. The relative effects of vibration frequency, vibration acceleration, nozzle size and nozzle inclination are compared with the goal of having the output mass flow rate monotonically change with one of these parameters. For the materials and parameters explored in this study, nozzle inclination is found to have the largest effect on mass flow rate output and has the desired monotonically changing relationship.

Keywords: Directed Energy Deposition; Capture Efficiency

Introduction

Powder-based Directed Energy Deposition (DED) processes are capable of creating high quality near net shape parts from a variety of materials. The process functions by directing powder feedstock material into an energy source while the process head and substrate move relative to each other, as shown in Figure 1. Typically, the powder is directed towards the melt pool via a carrier gas. Some powder does not end up being incorporated into the part. The ratio of the amount of powder incorporated into the part and the amount of powder dispensed is called the powder capture efficiency. The powder capture efficiency varies considerably, with some older machines having efficiency below 10% [1] and some newer systems having efficiency as high as 77% [2]. The push for higher powder capture efficiency comes mainly from the fact that wasted powder can significantly increase operating costs. Additionally, having a high and consistent capture efficiency makes process planning and parameter selection easier.

In an effort to increase powder capture efficiency, Wang and Li [3] developed a powder dispensing system that used vibration to dispense powder through a capillary. The dispensed powder slid down an incline and was directed into the melt pool. They were able to achieve 100% powder capture and saw improvements in surface roughness and porosity as well. Their work serves as inspiration for this work. One aspect not addressed in Wang and Li's research was the ability to control the mass flow rate of the powder being dispensed. Mass flow control is one of the three main process parameters in a DED process, and so any newly designed system should demonstrate the ability to control it. The goal of this study is to demonstrate that powder can be dispensed at controllable flow rates through a capillary using vibration.

An advantageous side effect of the proposed system is dramatic improvement in the time it takes to control and adjust powder flow. Conventional powder delivery systems like the one depicted in Figure 2 have several meters of tubing through which the powder flows before reaching the melt pool. This means that there can be a lag of several seconds between the time powder feed is started/stopped, and the time that change is seen at the deposition head. In contrast, a vibrating capillary system has the powder control located centimeters away from the melt pool so that the response time will be very fast.

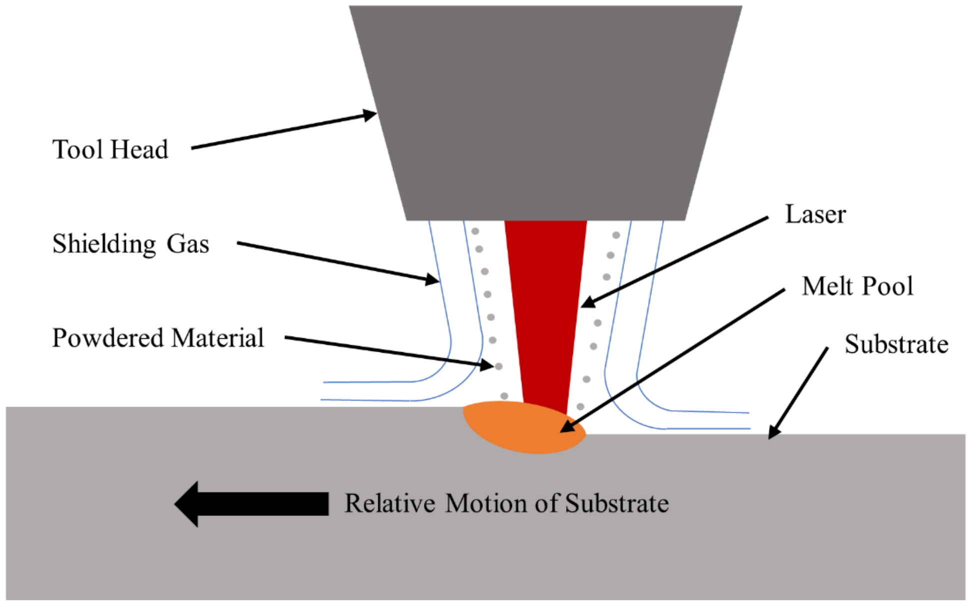

Figure 1: Illustration of a typical blown-powder DED system

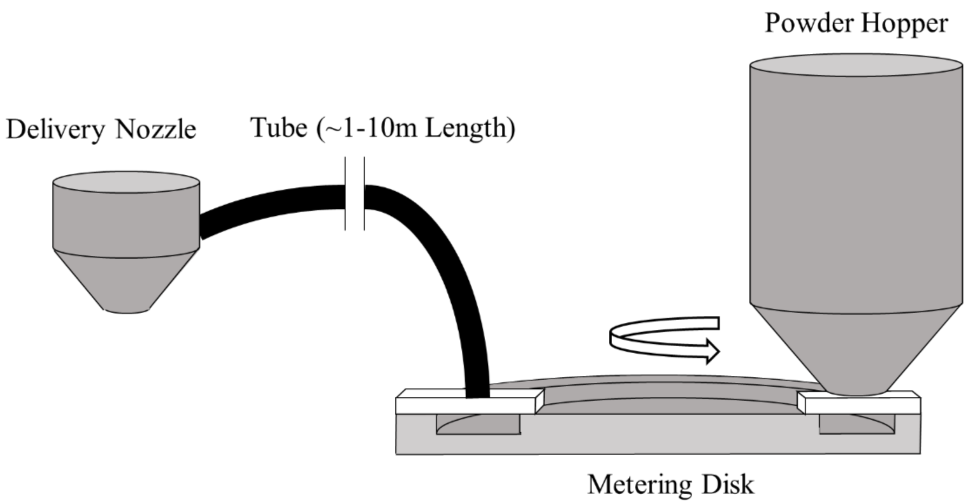

Figure 2: An example conventional rotating disk powder delivery system

Literature Review

Several studies have been conducted examining how powder flows through a capillary when vibration is applied. Researchers have studied the effects of capillary diameter, capillary length, vibration parameters (frequency, amplitude and acceleration), vibration direction and other factors on various types of powdered materials of different shapes and sizes for wide-ranging applications. Despite the wide range of approaches and applications, all authors seek to in some way understand the mass being released.

Matsusaka, et al. [4] used a vertical glass tube as a capillary to feed several tens-of-microns sized ceramic powders with low frequency vibration. They found that powder flow rate increased with vibration amplitude and that flow rate initially increased with increasing frequency but then leveled off at higher frequencies.

Kumar, et al. [5] used a vertical glass tube as a capillary to feed soda-lime glass particles in seven size ranges between 38-125 µm using high frequency vibration. They found that the powder flow rate initially increased with increasing vibration frequency, then hit a peak and dropped off.

Yang and Evans [6], [7] used a vertical glass tube as a capillary to feed metal powders with sizes less than 212 µm with low frequency vibration. Their results showed trends very different from the previously mentioned studies, where they found that mass flow rate decreased with both increasing vibration frequency and amplitude.

Though several studies on vibration-actuated powder dispensing have been conducted, no overall trends on how to control the mass being dispensed have emerged. With so many variables at play, different regimes of behavior have been observed. It is important to perform experiments with any system and material of interest to understand the behavior. Authors have speculated as to how particle-to-particle and particle-to-capillary interactions change as parameters are adjusted in the system. No extensive study has been performed to substantiate these thoughts.

Methods and Materials

With the goal of studying the performance and controllability of vibration powder dispensing, experiments were designed which studied the effects of vibration, nozzle diameter, and nozzle inclination on the mass flow rate output. A diagram of the experimental setup used in this study is shown in Figure 3a, and a picture of the actual system is shown in Figure 3b. The capillary that restricts the powder flow is a tapered stainless steel nozzle with inner diameter dimensions shown in Figure 3c. The nozzle is attached to a 3 ml plastic syringe which serves as the powder hopper. 10 grams of powder occupies the majority of the syringe volume and is sufficient to complete a 60 second run with consistent results. The syringe and nozzle are attached to a vibration actuation and measurement system (PI P840.2 piezo actuator, PI E610.0 piezo amplifier, Freescale FXLN8362Q accelerometer). When the system is operated, the powder falls from the nozzle onto a balance (H&C Veritas M314Ai), which sends mass data to a computer at set intervals. The impact force of an individual particle hitting the balance is smaller than the precision of the balance (0.0001 gram force) and occurs at a frequency that is filtered out by the balance. It is not considered in this work.

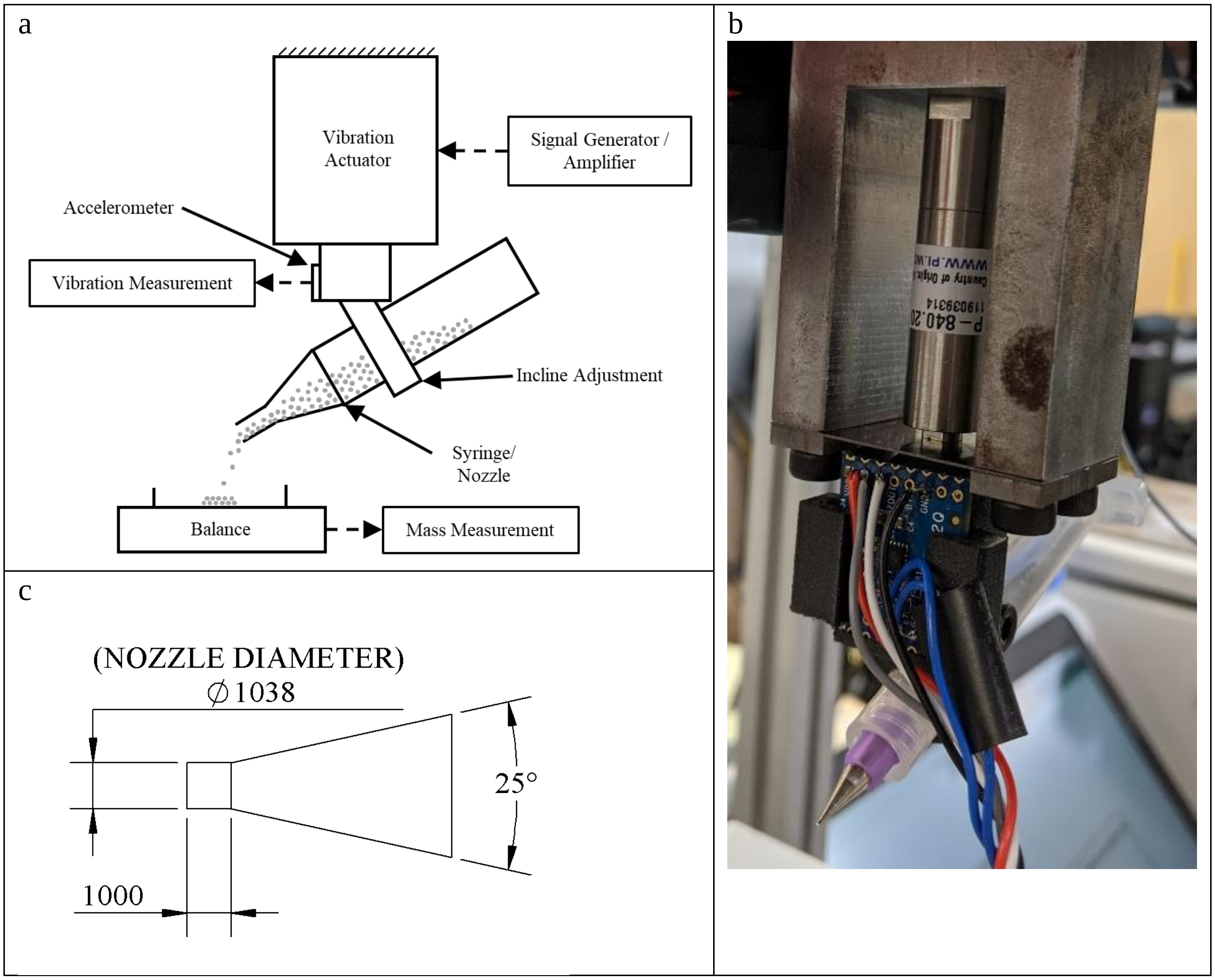

Figure 3: a) diagram of experimental setup b) picture of experimental setup c) inside dimensions of nozzle in microns

To perform a test, the following steps were taken. First, if the experiment had an inclined nozzle, the incline angle was set. Second, 10 ± 0.2 g of 316L stainless steel powder (44-106 µm, LPW-316-AAAW) was loaded into the 3ml syringe. This syringe size and powder mass combination was selected. Third, vibration was turned on and data was collected. Vibration acceleration measurements were collected at ten samples per cycle for twenty cycles in both the vertical and horizontal directions. Cumulative mass measurements were taken for 60 seconds at 0.1 second intervals.

Mass flow rate was calculated by performing linear regression on the cumulative mass versus time measurements. The slope of the fitted line is the best-fit mass flow rate, and the R^2 statistic can be used to gauge the consistency of the mass flow rate. Peak-to-peak acceleration values were calculated as the difference between the largest and smallest values in each acceleration measurement. The frequency of the vibrations was verified using a fast Fourier transform.

Results and Discussion

The first experiment aimed to determine the appropriate ranges of peak-to-peak vibration acceleration (10-100 m/s^2), vibration frequency (100-1000 Hz), and nozzle diameter (660-1346 µm straight and 335-437 µm tapered). The initial tests were all performed with the nozzle oriented vertically. For a relatively free-flowing powder in the 44-106 µm size range, the vertical nozzle orientation led to all-or-nothing powder feeding behavior. With smaller nozzle diameters, powder would often not flow at all. With larger diameter nozzles, powder flow often continued even after vibration was stopped. In these cases, it was impossible to achieve appreciable control over the mass flow rate.

Observing this behavior, the next experiment was devised to add nozzle inclination tilt angle as a variable (defined as the angle from horizontal). The second experiment aimed to screen the four variables being examined to see which would be the most useful for implementing mass flow rate control. The factors and levels used are shown in Table 1. The ANOVA main effects plot of the powder mass flow rate versus each of the four controllable factors is shown in Figure 4. These results indicate that nozzle inclination angle has the largest effect on powder flow rate. The nozzle inclination angle is easily adjusted and is well suited for use in an eventual machine design where a motor can adjust tilt angle on the fly to increase or decrease the powder dispensing rate. Nozzle diameter has a significant effect as well. Nozzles can be changed between printing runs, however, nozzle diameter cannot easily be changed on the fly during a print run. In that sense, nozzle diameter is perhaps less well suited for use as the main controllable factor for increasing or decreasing powder flow rate during a print run. Vibration frequency and acceleration both have less pronounced effects on powder flow rate and will not be used for control purposes.

Table 1: Factors and levels used in screening experiment

Factor	Vibration Acceleration (m/s^2)	Vibration Frequency (Hz)	Nozzle Inclination (°)	Nozzle Diameter (µm)
Level 1	31.6	316	22.5	680
Level 2	100	1000	32.5	1038
Level 3	-	-	42.5	-

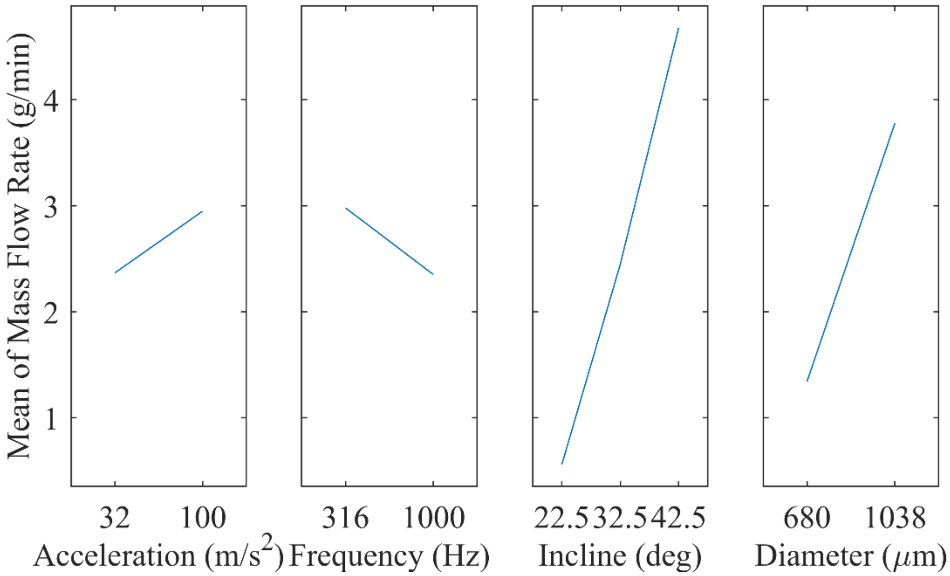

Figure 4: Main effects plot of screening experiment

The last experiment aimed to look at nozzle inclination and diameter in greater detail. Furthermore, the repeatability of flow rate between trials was also studied. Figure 5 shows the data collected for three different diameter nozzles across five levels of inclination with six replicates (error bars are one standard deviation in each direction). The data shows that mass flow rate increases nearly linearly with nozzle inclination, and different diameter nozzles can be used to give different flow rate ranges within a given print run.

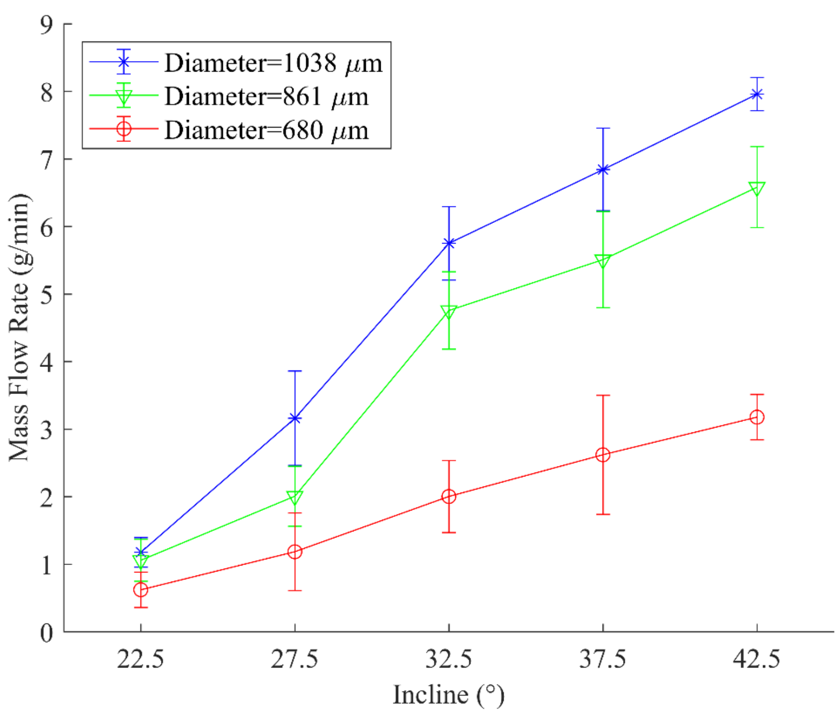

Figure 5: Mass flow rate versus nozzle incline angle results

It is important to note the time scale that the variance in the mass flow rate shown in Figure 5 occurs in. The measurements in Figure 5 are the average of experimental runs performed on different days, which could differ because of environmental changes in temperature or humidity. These conditions were intentionally not controlled to assess this day-to-day variability, which could be dealt with using calibration. However, within each experimental run, the second-to-second variance is significantly lower, with linear regression of each run having an R^2 value greater than 0.99.

Conclusions

Given the wide range of behaviors in vibration powder dispensing systems in the literature, the conclusions drawn from this work should be applied close to the context of the parameters used in this study: 44-106 µm 316L stainless steel powder, 100-1000Hz frequency and 10-100m/s^2 peak acceleration vibration, and 681-1038 µm stainless steel tapered nozzles.

- A vibration-actuated powder dispensing system was constructed which gave a range of useful mass flow rates.
- Nozzle inclination proved to be the most influential parameter in controlling mass flow rate. With the nozzle and powder used in this study, vertically oriented nozzles gave only on-off mass flow rate control. The monotonically increasing relationship between nozzle incline and mass flow rate is promising as the basis for a control system in a machine design. This is a novel finding.
- Nozzle diameter has a significant effect on powder mass flow rate, but it cannot be changed on the fly during a print run, and it is less well suited to be controlled in a machine design. The ability to change nozzle diameter by switching nozzles between print runs to get different achievable flow rate ranges is still useful though.
- There is some variability in mass flow rate looking at runs performed on different days, but the second-to-second variability of mass flow rate in an experimental run is extremely small.
- While many studies in the literature used changes in vibration to achieve changes in mass flow rate, the effects of vibration were relatively small compared to the effect of nozzle incline angle.
- With the successful demonstration of mass flow rate control in vibration-actuated powder dispensing, gas-free powder delivery to the melt pool can be studied.

Powders having different shapes and size distributions from the ones used in this preliminary study will not necessarily exhibit the same flow behavior through capillary feed tubes as that which is shown in Fig. 5. However, the test apparatus and experimental flow calibration procedure demonstrated in this work make it easy to generate flow data similar to that shown in Fig. 5 for any other powder and nozzle combinations.

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