Drop-On-Demand Ink Jet Printing for Three Dimensional Printer Application

by

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Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Abstract

This project aims to demonstrate feasibility of drop-on-demand (DOD) ink jet printing for application to three-dimensional printing. The DOD jetting device that was designed, built, and tested for this project used a cylindrical piezoelectric as both the fluid chamber and mechanical transducer. Drops were successfully generated using this device, though with drop velocities and volumes lower than expected, probably due to air bubbles trapped inside the fluid chamber. Operating ranges for the jetting device were noted, and seemingly optimal settings were recorded. Despite the somewhat limited scope of the project, feasibility was established for using drop-on-demand jetting for printing fluids non-intrusively.

Thesis Supervisor: Emanuel M. Sachs
Title: Associate Professor

Acknowledgments

With gratitude and appreciation I'd like to acknowledge Jim Serdy, for his insight, wisdom, and extraordinary perspective in so many fields, from DOD jetting to solar energy to the plight of crumbling Russia. I'd also like to thank Fred Coté for his patient machining instruction and advice, and, of course, Professor Sachs, for his constant ideas and guidance.

I will always be grateful to my parents for financing my education and for their general support throughout — from the freshman year struggle, through the long year in Russia, to finally completing this thesis — thanks for everything!

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Chapter 1

Introduction

1.1 Background

The manufacturing processes that are widely used today usually involve some type of material removal or deformation. These processes, when applied to manufacturing parts with complex geometries, are typically very time-intensive and produce much waste. However, we are now entering a manufacturing era in which parts can be built up incrementally, enabling greater customization, less machining time, and much less waste. Three-dimensional printing is one such rapid prototyping process. After a person designs a part on a CAD system, she sends it to a slicing algorithm, which gives the printer the information necessary to build each layer. Using ink-jet printing techniques, a nozzle dispenses droplets of a binding fluid onto a bed of powder in the appropriate places, the piston on which the powder bed sits drops incrementally, more powder is spread, and the next layer is printed. The three-dimensional printing process is illustrated in Figure 1-1.

This process can be extremely useful in producing ceramic molds for cast metal parts, shortening the turnaround time from several days to just a few hours. Also, there has been success in printing parts out of metal powder, which can then be sintered.

There are also biomedical applications for this technology, such as manufacturing time-release capsules for in vitro implants. These drugs have labyrinith-like struc-

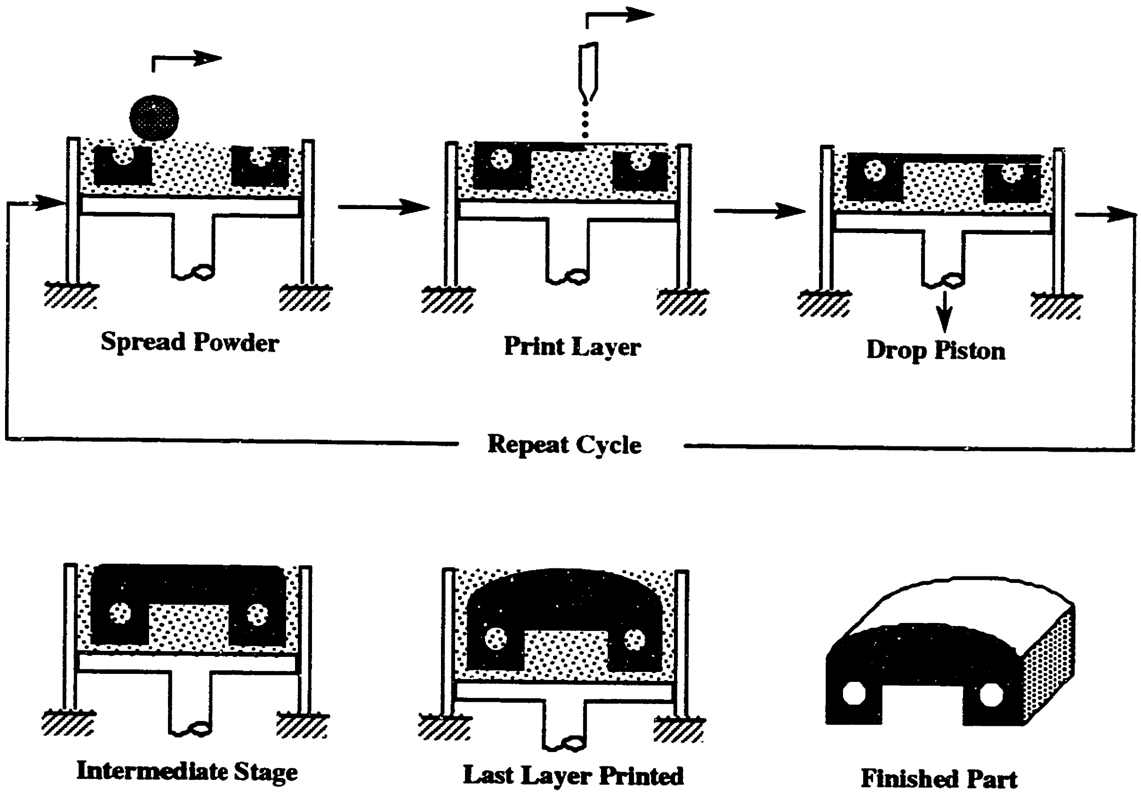


Figure 1-1: The 3-D printing process [Williams, p.14]

tures with many pockets of the active drug which are gradually exposed and metered into the bloodstream; they typically have very complex geometries and are inherently difficult to make. However, if these were printed instead of formed and filled, the cycle time could be significantly reduced. especially if several nozzles worked simultaneously, each printing a different substance.

1.2 Continuous vs. Drop-On-Demand Jetting

The current method of dispensing binder droplets for 3-D printing is called continuous jetting. In this process a continuous stream of fluid degenerates into a series of droplets, either by the natural phenomenon as described by the Rayleigh instability mechanism [Rayleigh, 1878], or by external forcing. The resulting stream of droplets then passes between high voltage capacitor plates which electrostatically charge and deflect that proportion of the droplets which are not intended to be printed. Due to the necessity of electrostatically altering the printed substance in continuous jetting, it

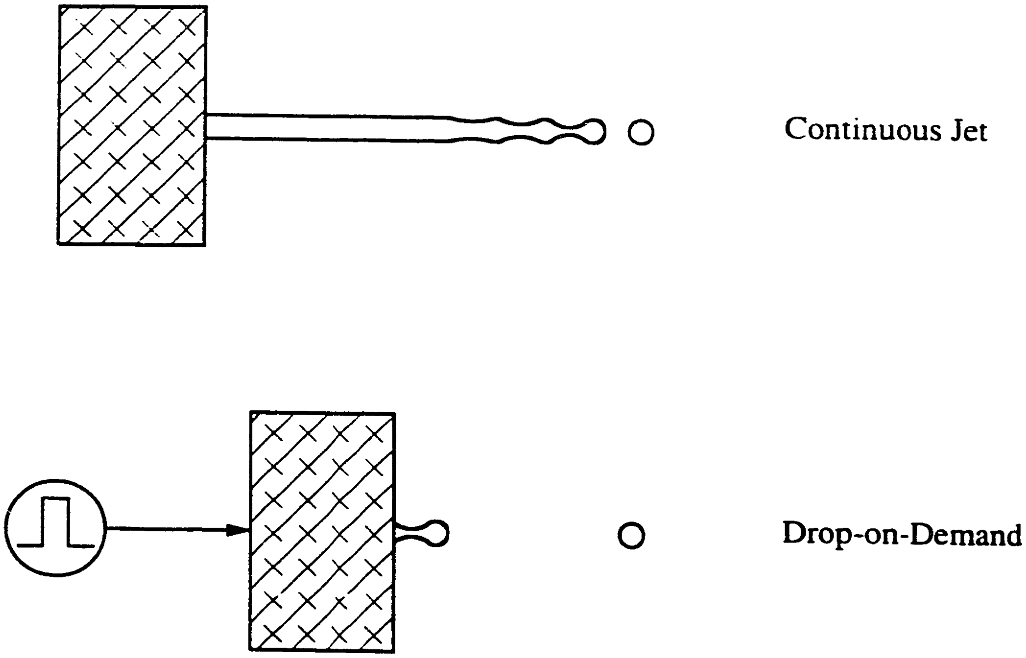


Figure 1-2: The continuous jet system forms a fluid stream which breaks up into droplets, while the drop-on-demand system ejects a single droplet in response to an input signal [Duthaler, p.13].

is not an appropriate means of printing sensitive substances such as pharmaceuticals. Also, continuous jetting accumulates a large amount of waste, also not desirable when dealing with very expensive chemicals. Thus a non-intrusive, low waste means of jetting is needed. To find such a means is central to this research.

A drop-on-demand system is one which dispenses one droplet at a time, and only upon command. Most commercial applications of drop-on-demand jetting use thermal ink-jetting, in which a heat flux causes local nucleate boiling, resulting in a vapor bubble which expels the droplet in front of it. However, in view of the goal of developing a non-intrusive system, this study uses mechanical instead of thermal or electrical forces on an incompressible fluid to eject a droplet.

1.3 Objectives

The objective of this research was to design. build. and test a drop-on-demand printing device. ascertaining the operational characteristics. with the intent of applying this information to a future 3-D printer printhead. The nozzle's design was to use a cylindrical piezoelectric as the fluid transducer.

In addition to the design and fabrication of the jetting device. theoretical and experimental work was to be done on the piezoelectric's driving waveform. to find the optimal parameters for jetting fluid.

Chapter Two explains the design considerations for both the nozzle and the waveforms. Chapter Three describes the nozzle's fabrication and the testing apparatus, and Chapter Four discusses the test results. Finally, Chapter Five makes final conclusions and proposes directions for future study.

Chapter 2

Design Considerations

2.1 Nozzle Design

2.1.1 Cylindrical Piezoelectric

Many DOD printing devices use piezoelectric elements as fluid transducers. In these experiments the piezo element acted as both the transducer as well as the fluid chamber; this ensured maximum contact and thus better response between the mechanical constriction and the fluid. The cylindrical piezoelectric used in these experiments was made of PZT-5H ceramic, a piezo material designed for applications requiring fine movement control, such as hydrophones and ink jet printers. The silvered inside and outside surfaces acted as the two electrodes. A voltage drop between the two surfaces produced a mechanical deformation in the element. the magnitude of which depended upon the voltage applied and the piezo material. This deformation created a pressure and volume change of the fluid inside, causing the fluid to be ejected through orifices on either end of the piezo tube.

2.1.2 Orifice Sizes and the Fluid Flow Model

In order to regulate the fluid flow through the cylindrical chamber, endcaps with small orifices were needed, one for the intake and one for the outlet. In this case, a 25 μm orifice was chosen for the inlet, and a 50 μm orifice was chosen for the outlet, based upon the theory that when the chamber constricted. fluid would be expelled in both directions. and by designing the intake orfice to be smaller (and thus with a higher impedance). that would ensure that the majority of the fluid displacement would be ejected with only a small amount returning to the fluid reservoir. This conclusion follows from looking at the following model.

Figure 2-1 shows the cross-section of a fluid chamber which has two orifices. one having twice the radius of the other. Using inviscid. steady flow as an approximation of our situation, the velocities of the fluid being ejected from either orifice will be equal. The total fluid expelled will be equal to the piezo's volume displacement, and the proportions of the total which are ejected from each orifice will depend on the orifice area. in accordance with the equation

$$Q = VA \tag{2.1}$$

where Q is the volumetric flow rate. V is the fluid velocity, and A is the orifice area. Thus, there will be four times the flow out the larger orifice than out the smaller. The streamlines in the schematic show the characteristic streamlines of this phenomenon; there will be a stagnation point approximately 1/5 of the total length away from the smaller orifice, and the fluid position with relation to this point will determine in which direction it is ejected.

The viscous case arises when the boundary layer. created by the fluid being ejected through the orifice, builds up to the point where it impinges on the flow. This case is governed by the equation

$$\delta = \sqrt{\nu t} \tag{2.2}$$

where δ is the thickness of the boundary layer. ν is the fluid's kinematic viscosity. and t is the time duration of the ejection. Using water and a pulse duration of 3 msec. the boundary layer is about 50 μm, the same as the diameter of the orifice. This suggests that viscous forces will dominate in giving the fluid a parabolic profile, but to a rough approximation. the proportions of fluid being ejected in either direction will remain the same.

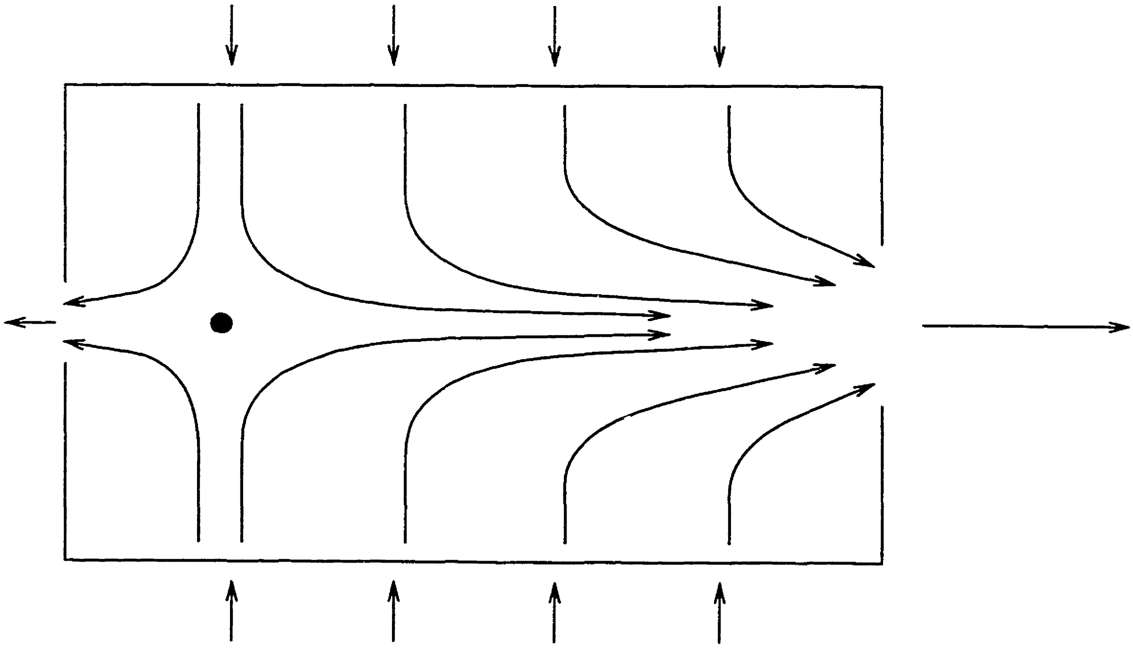


Figure 2-1: The inviscid, steady state case predicts that 4/5 of the total fluid will be ejected from an orifice twice the diameter of the other upon constriction. The direction of fluid flow depends upon its relation to the stagnation point.

2.1.3 Requirements for Ejection

Ballistic ejection requires that the kinetic energy of the displaced fluid overcome the surface energy of the meniscus in the orifice, which is a function of the fluid's surface tension σ and the orifice radius r:

$$\frac{4}{3}\pi r^3 \rho v^2 = 4\pi r^2 \sigma \tag{2.3}$$

where ρ is the fluid density and v is the fluid velocity at the orifice. Rewriting this equation gives

$$v = \sqrt{\frac{3\sigma}{\rho r}} \tag{2.4}$$

which, when evaluated for water, prescribes the minimum meniscus velocity to be 3 m/s for successful ejection. This is the "compression" stroke of a drop-on-demand device; the other four phases in the droplet ejection cycle are illustrated in figure 2-2.

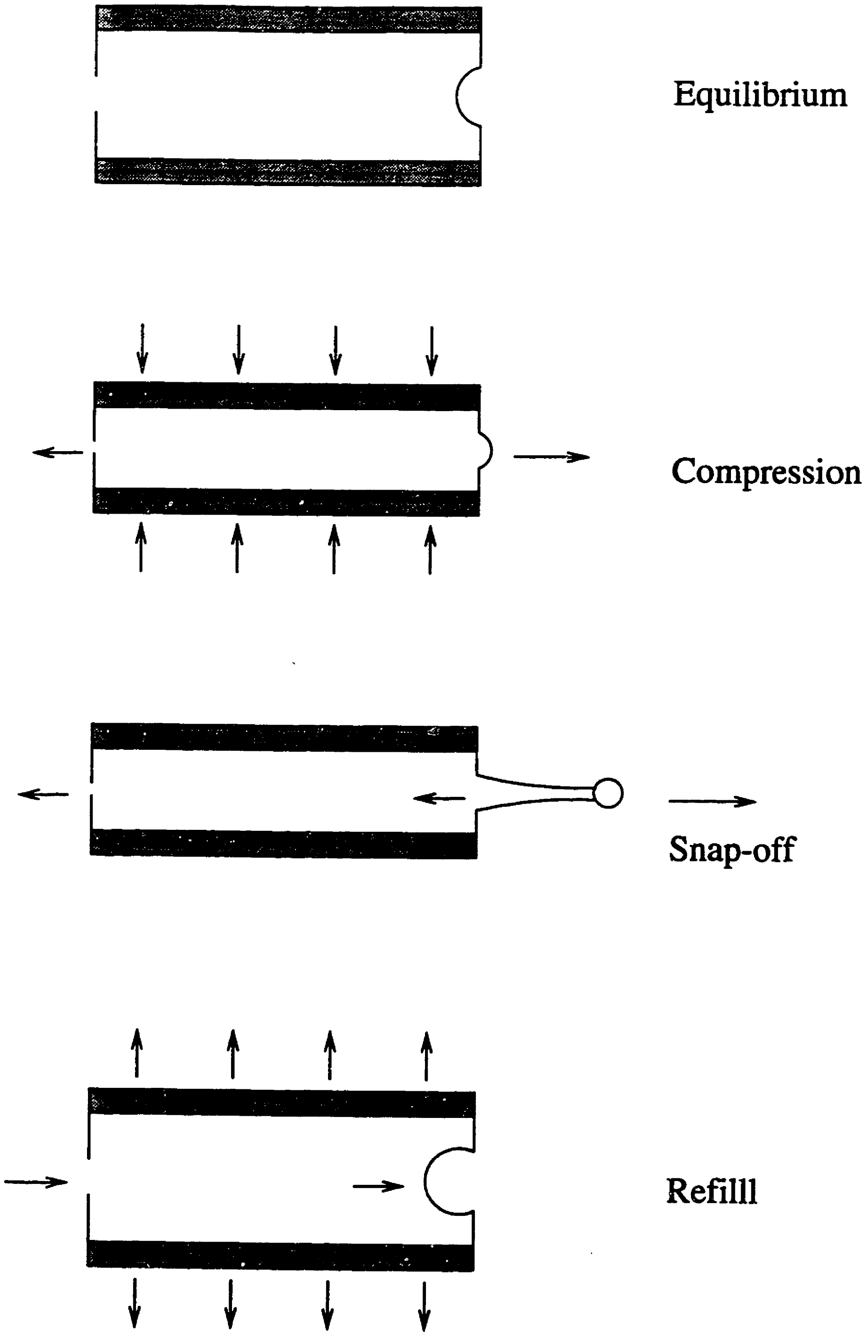


Figure 2-2: The four phases of the DOD jetting cycle: equilibrium, compuression, snap-off, and refill

2.1.4 Droplet Size

Assuming incompressible flow, it is possible to predict the diameters of the ejected droplets. Based on the piezoelectric's material properties and geometry, we can predict the cylinder's change in radius, Δr, for a given voltage V and piezo wall thickness t:

$$\Delta r = V(\frac{|d_{33}|}{2} + |d_{13}|(\frac{r}{t})) \tag{2.5}$$

. In this equation, d_{33} and d_{13} are piezoelectric charge constants in the radial and axial directions, respectively. They represent $\frac{strain}{appliedfield}$ for a given piezoelectric material. The first term on the right hand side captures the circumferential strain effect, and the second captures the effect of the increase in wall thickness of the thin-walled tube. Using this Δr we can calculate the piezo's volume change, which is equal to the volume of displaced fluid. Assuming spherical droplets, the diameter can be calculated from this predicted volume change.

2.2 Ejection Models and Waveform Design

There are two generally accepted models for the fluid pulse traveling through the cylindrical chamber to eject a droplet: the displacement model and the acoustic model.

2.2.1 Displacement Model

The displacement model takes the fluid as incompressible so that the volume change of the piezoelectric acts as a single, piston-like displacement, and accounts for all of the fluid volume displacement, mostly in the form of the ejected droplet. It neglects all effects of wave reflections because it assumes that every fluid wave travels the length of the fluid chamber at the speed of sound and is ejected before the next wave is generated. This assumption served to set some of the waveform parameters. Given that

$$t_{prop} = \frac{l}{c_w} \tag{2.6}$$

were t_{prop} is the amount of time necessary for a wave to propagate the entire length of the 1/2" piezo used in these experiments. l is the piezo length, and c_w is the speed of sound in water. the minimum time between pulses would have to be $8.5\mu s$, the reciprocal of which determines that the maximum driving frequency, 118 kHz. At this frequency, each wave would just barely make it out the orifice before the next was generated. However, the time between pulses must also take into account the meniscus recovery time, since the nozzle can't eject another drop until the refill phase is complete. In a similar DOD nozzle assembly made by J.D. Beasley, the experimentally observed time for this recovery was on the order of 40 to 60 μs [Beasley, p. 80], which, when added to the minimum propagation time, decreases the maximum driving frequency to about 15 kHz. A detailed theoretical and experimental analysis of this model is available in Beasley's "Model for Fluid Ejection and Refill in an Impulse Drive Jet."

2.2.2 Acoustic Model

The acoustic pressure wave model takes the cylindrical chamber as a one-dimensional waveguide; the piezo's constriction generates a pressure wave that moves at the speed of sound through the fluid. When the wave encounters any kind of obstruction or change in impedance, part of the wave is transmitted while part is reflected (see Fig. 2-3). It is the combination of the arriving waves and their reflections at the nozzle that then push out a droplet.

Drop-on-demand ejection in the acoustic regime takes place at higher frequencies than are used for the displacement regime; Bogy and Talke cited a range of 1-15 kHz. Their observations of meniscus distortion relating to fluid cavity length led them to believe there was a correlation with the acoustic waves created by the tube's contraction and expansion[Bogy and Talke, p.316]. Their analysis concluded that, when operating in this regime, there were wave reflections enough to eject two droplets for each pulse (see Fig. 2-4), and they recommended synchronizing these secondary droplets not only to keep them distinct from the subsequent droplets, but also to make use of the extra droplet [Bogy and Talke, p.320].

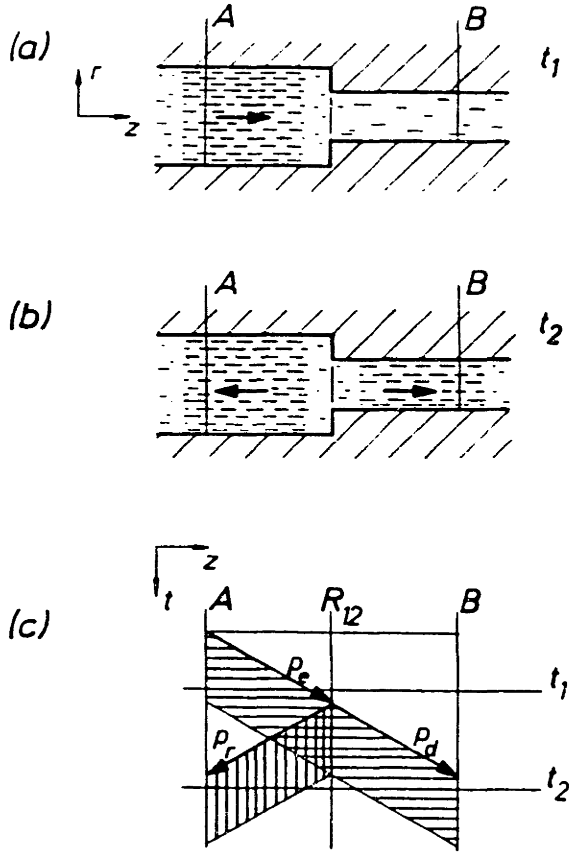
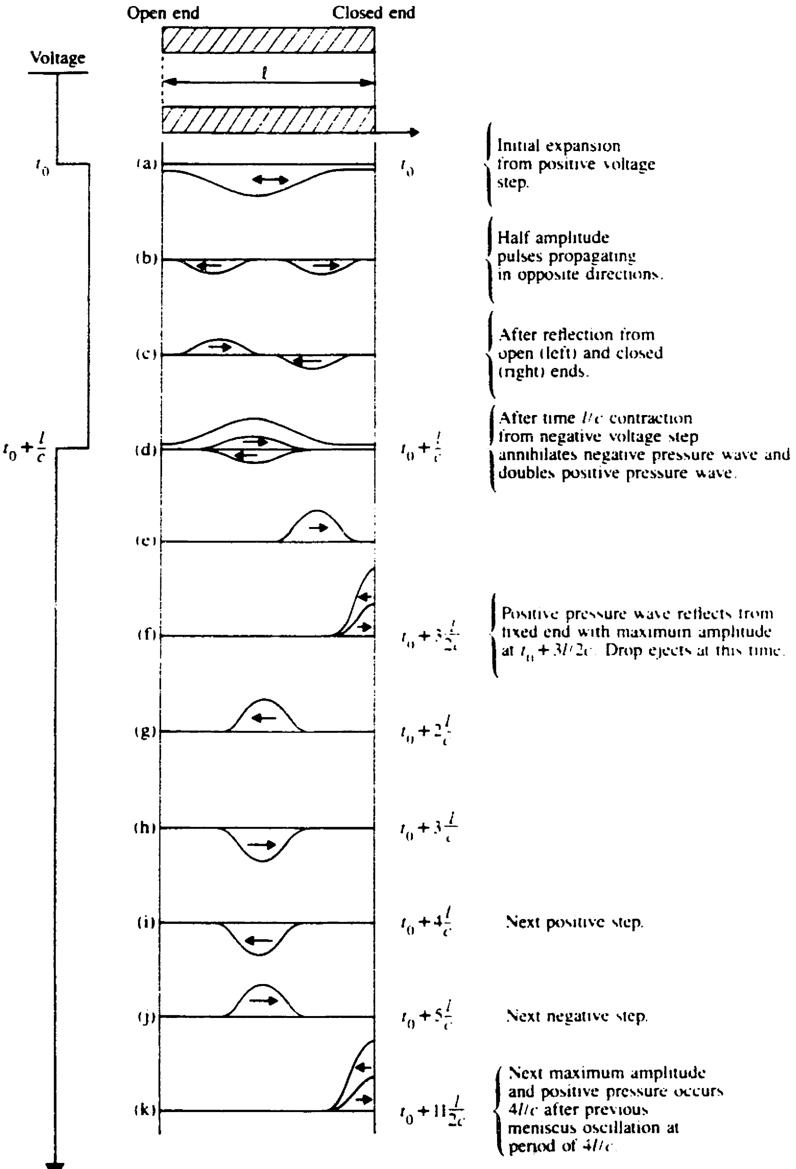


Figure 2-3: Response to a pressure step: (a) the arriving pressure wave, (b) transmitted and reflected waves, (c) time-path diagram of the wave split [Heinzl and Hertz, p.119].



Initial expansion from positive voltage step.

Half amplitude pulses propagating in opposite directions.

After reflection from open (left) and closed (right) ends.

After time l/c contraction from negative voltage step annihilates negative pressure wave and doubles positive pressure wave.

Positive pressure wave reflects from fixed end with maximum amplitude at $t_0 + 3l/2c$. Drop ejects at this time.

Next positive step.

Next negative step.

Next maximum amplitude and positive pressure occurs $4l/c$ after previous meniscus oscillation at period of $4l/c$

- Optimum pulse width $= l/c$.
- Meniscus oscillation period $= 4l/c$.
- Maximum velocity period $= 4l/c$.

Figure 2-4: Propagation and reflections of initial pressure pulse: open end = inlet, closed end = outlet [Bogy and Talke, p.319]

2.2.3 Waveform Characteristics and Design

The driving waveform for a droplet generator is a crucial factor in successful jetting. However, the great number of variables intrinsic to any waveform and the many ways in which they affect each other make it difficult to define optimal parameters. The primary parameters for a DOD nozzle are the pulsewidth, the time between pulses (the reciprocal of which is the frequency), the voltage amplitude, the wave's rise time and fall-off time, and the wave's shape.

The boundary case frequency, previously determined by Equation 2.6, is strictly that: a boundary. In reality, DOD nozzles tend to operate at significantly lower frequencies, usually less than 2 kHz.

The pulsewidth greatly affects the drop velocity. Equation 2.1, in conjunction with

$$Q = \Delta\mathcal{V}\frac{1}{t_p} \tag{2.7}$$

where $\Delta\mathcal{V}$ is the cylindrical piezo's volume change and t_p is the pulsewidth time, gives the equality

$$VA = \Delta\mathcal{V}\frac{1}{t_p} \tag{2.8}$$

from which we can calculate the optimal pulsewidth for a target velocity. For a reliable, steady stream, we set the target velocity range to be 3-10 m/s, which determines the optimal pulsewidth range to be 1-4 msec (taking into account the maximum 20% fluid loss back through the inlet orifice). This represents the total pulse time, and it includes the wave's rise and fall times. Rise times for DOD devices are typically very short (4% of the total pulsewidth was used successfully by Beasley), followed by a slow decay to 0 to allow time for the chamber to refill. The wave's fall-off time can start either directly after the completion of the rise time, or after a dwell time.

The maximum voltage amplitude is determined by the piezoelectric material; at voltages higher than a certain point the piezo starts to degrade and its performance decreases. A maximum of 100 volts is the upper bound for the PZT-5H ceramic piezo used in these experiments. Also, other research has concluded that the amplitude needed to eject a drop decreases if the piezo cylinder length is increased [Bogy and

Talke. p. 315].

The shape of the driving waveform may or may not have any significant effect on the performance of a DOD nozzle. Certainly, the components of waveshape such as rise time, fall-off time, and total pulsewidth affect droplet generation, but it is not clear what effect the actual shape has. The study by Gerhauser et al. concludes that drop volume and velocity are greatly affected by pulsewidth and voltage amplitude, but are nearly waveshape independent [Gerhauser et al., p. 110]. They claim that the velocity variations as a function of frequency are independent of waveshape because "a pressure pulse that ejects the drop at the nozzle is the integrated effect of the distributed local pressure waves in space and time...a result of the superposition of all pressure pulses within the drop generator from all previously ejected drops" [Gerhauser et al., p. 110]. However, it should be noted that all of the waveforms that they tested were symmetric; it is possible that an asymmetric, more complex waveshape could affect droplet generation.

Chapter 3

Apparatus: Nozzle Fabrication and Waveform Generation

3.1 Nozzle Fabrication

The main component of the nozzle was the 1/2" long, 1/4" diameter cylindrical piezoelectric. It was made of PZT-5H ceramic, a material used for applications requiring fine movement control, from hydrophones to ink-jet printers. Aluminum endcaps were bonded to either end of the cylindrical chamber using RTV silicone adhesive. In the centers of these endcaps were tiny holes that acted as fluid channels to the chamber, and ruby nozzles with very small orifices were countersunk into either endcap. The end designated as the outlet had a 50 μm orifice, while the intake had a 25 μm orifice. Since the piezo's inner and outer surfaces act as its electrodes, a thin wire was wrapped around the outside of the cylinder, and another thin wire was soldered onto the inside surface and threaded through a small hole in the inlet's endcap. This then passed through a hole in the supply line, a length of flexible, rubber tubing which fit around the perimeter of the inlet endcap (see Figure 3-1).

This set-up seemed to work fine until the device was left idle for a period; then tiny clogs developed within the chamber, possibly from particulates corroded from the internal solder bond. This required a complete disassembly of the tiny apparatus, a thorough cleaning, and a complete reassembly, which proved to be an extremely

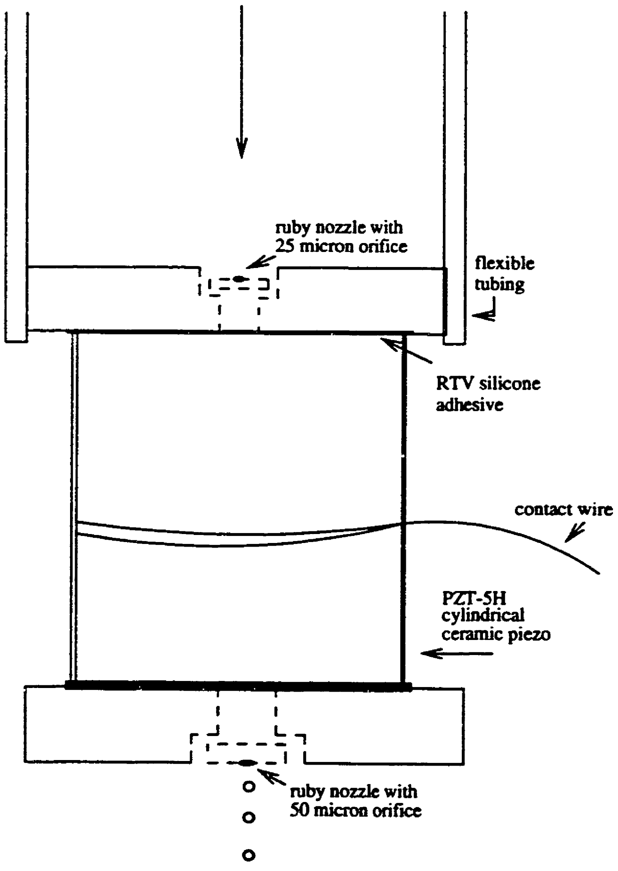


Figure 3-1: Basic nozzle assembly

time-consuming task, since the adhesive takes 24 hours to cure completely. It became clear that a more efficient means of assembly and disassembly were needed.

A simple clamping device was made (see Figure 3-2) that held the endcaps securely against the ends of the piezo, each separated by a thin piece of rubber which acted as a gasket. This greatly reduced the amount of time needed to clean out the fluid chamber.

3.2 Waveform Generation

After determining the parameters of the waveforms to be used in the experiments, the waveform was generated using an HP Arbitrary Waveform Generator. This signal was split into two parts: the standard output signal and the TTL signal. As shown in Figure 3-3, the standard output signal was amplified to the appropriate level, and then directed into the nozzle assembly. The TTL signal, a digital pulse of the same

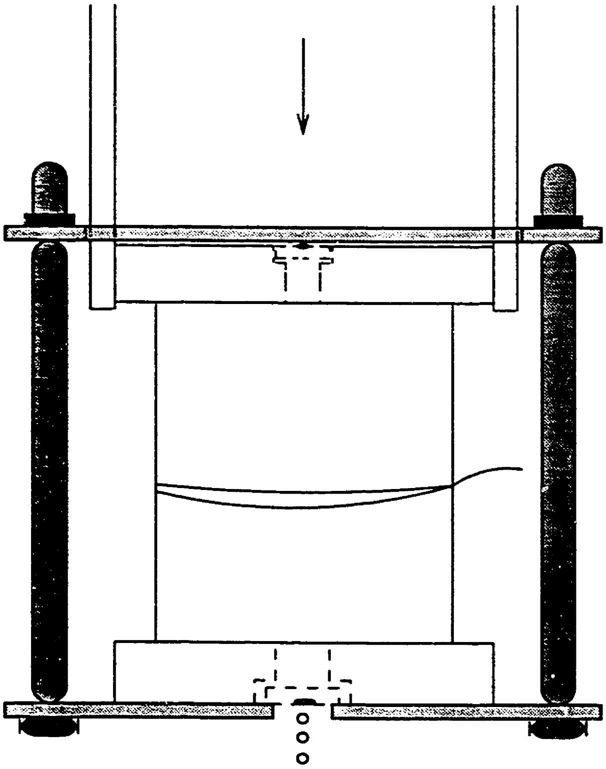


Figure 3-2: Modified nozzle assembly – with clamp

frequency as the standard output signal, was sent to the strobe light circuitry which effectively synchronized the strobe flashes with the output signal, allowing the camera and VCR to detect and record single droplet ejections.

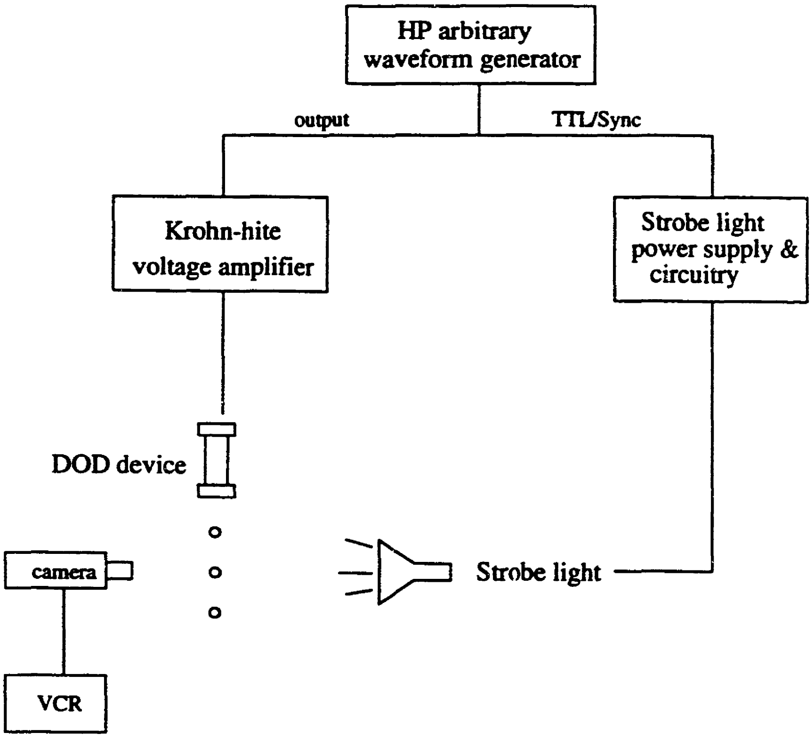


Figure 3-3: Equipment setup

Chapter 4

Experimental Results and Discussion

4.1 Droplet Generation

Drops were successfully generated using this device for a wide range of frequencies, voltages, and pulsewidths. During one set of tests, there was some semblance of jetting from as low as 2 Hz all the way up to 1100 Hz. Also, drops were jetted from 40 volts up to the 100 volt maximum for the piezo material. 50 volts seemed to be an optimal setting; this voltage was high enough to generate drops consistently, yet low enough that the nozzle was not overdriven, resulting in multiple streams (discussed below). This is in agreement with what Johnson and Bower call the "50 V standard" [Johnson and Bower, p. 176]. Likewise, 200 Hz seemed to be an optimal frequency; at this level there was one strong, steady stream, with only an occasional secondary stream (see Figure 4-1).

Due to the great number of variables at work in the ink-jet process, most of these tests were done using a simple square wave. This is a good generic wave to use because of its short rise time and easily-varied pulsewidth. While holding a voltage and frequency constant, it is easy to sweep through a range of duty cycles to determine the optimal pulsewidth. (Duty cycle is the ratio of pulse time to non-pulse time within the wavelength; a 20% duty cycle describes a wave with a thin, square spike.) At

Figure 4-1: Test results - droplet ejection at optimal settings, one stream

Figure 4-2: Test results - droplet ejection at high frequency. Note the multiple, smaller streams to the left of the main stream.

200 Hz there seemed to be little difference in jetting performance between 20% and 80% duty cycles: however, these two settings prescribe a pulsewidth range of 1-4 msec, exactly the optimal pulsewidth range calculated from Equation 2.8, so it is not surprising that all these duty cycles yielded good results. With respect to waveshape, drops were successfully generated using sine waves as well as an arbitrary waveform similar to an exponential rise wave, at voltages and frequencies similar to the ones used with square waves. However, there seemed to be no clear performance difference among the different waveshapes tested. The research conducted by Gerhauser et al. similarly concluded that drop volume and velocity are nearly independent of waveshape [Gerhauser et al., p.110]. However, it should be noted that the waveshapes they tested were the symmetric waveforms available on their signal generator; it is probable that more effective system response could be realized by tailoring waveshapes using an arbitrary waveform generator.

4.2 Droplet Stream Characteristics

Probably the most prominent of the droplet streams were their unsteady, curving shapes. Ideally, a stream of droplets would be straight and steady; it is extremely important, especially for 3-D printing, that it be possible to predict the drops' trajectories, which are already distorted by the printhead's movement across the powder bed. The fact that the streams generated in these experiments were not straight implies that the drops' velocities were less than expected; their accelerations upon ejection would not be adequate to carry them to the powder bed. It should be noted that current standards of stream straightness are based on comparisons with streams generated by continuous jetting; DOD devices typically have a much smaller spacing between the jetting orifice and the target, on the order of 1/8" for commercial thermal ink-jet printers, and thus the length of the stream that is straight need not be very long. However, the streams that were generated in these experiments did not even have this minimal length of straightness, which implies that the drops were being ejected at inadequate velocities. This may be the result of a small air bubble inside

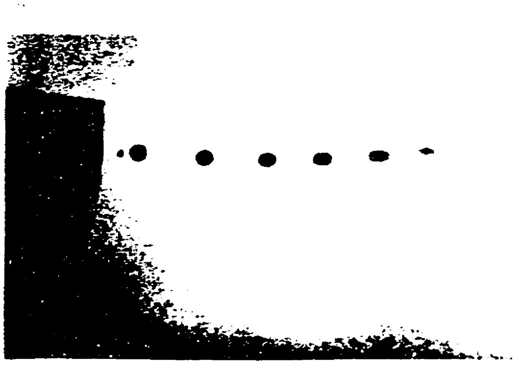


Figure 4-3: Example of unsteady stream due to excess air bubble in fluid chamber [Johnson and Bower, p.177].

the fluid chamber, an example of which is shown in Figure 4-3. [Johnson and Bower, pp. 177-8]

Section 2.1.4 discussed how to predict drop diameters from the piezoelectric's material properties and geometry. For the piezo used in these experiments at 50 volts, we predict drops to be approximately 300 μm in diameter. The drops observed and measured (via video camera and monitor), however, were on the order of 100 μm. This, too, is probably due to air trapped inside, which decreases the fluid's incompressibility and therefore the ejection volume.

It was observed that for a constant voltage setting, as frequency was increased, multiple, smaller droplet streams appeared. One larger, dominant stream was always visible. but was accompanied by two to four smaller, mist-like streams as frequency increased. This phenomenon may the be effect of an over-driving voltage or of a too-short pulsewidth. As shown in Figure 4-4. there are regimes of the drop formation characteristics that are affected by voltage amplitude and pulsewidth. According to this graph, unstable ejection due to the presence of air bubbles in the fluid chamber occurs in region D, and a thread-like ink mist is generated in region C. Since both of these characteristics were observed, it is possible that the driving voltage was too high or the pulse duration was not right. It should be noted that Kutami et al. used a different type of droplet generator, so the the actual axis numbers are not necessarily applicable for our case; however, the graph does clearly show that these distinct

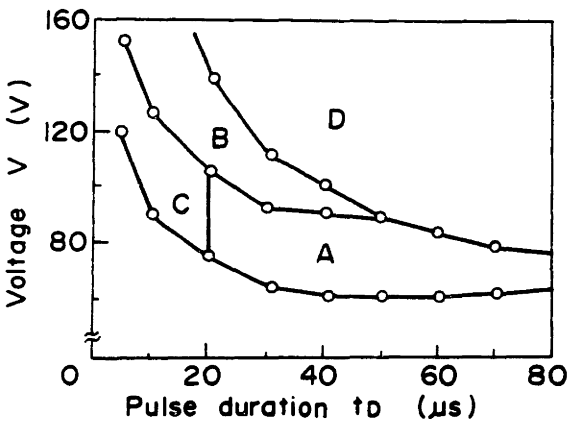


Figure 4-4: Types of droplet formation versus pulse duration and voltage: (A) no satellite or high-speed satellite, (B) low-speed satellite, (C) thread-like ink mist, (D) air-bubble absorption [Kutami et al., p. 109].

regions exist and have non-uniform relations to one another and to the increasing X and Y axes.

Chapter 5

Conclusions and Recommendations for Future Work

The successful generation of drops in this study shows that there is significant potential for DOD jetting using cylindrical piezoelectric elements as fluid chambers as well as transducers. Although the reliability of the ejected stream was tenuous, the experiments clearly demonstrated the feasibility of the technology. While the only fluid tested in this research was water, there is good reason to believe that the same technology could be used with more viscous fluids such as binder. In fact, many other studies used ethylene glycol or some other water/glycol mixture as the operating fluids and were successful in jetting them. Attempting to jet other, more viscous fluids seems to be an appropriate direction of future research.

Another recommendation for further studies is to construct the jetting device such that the inlet orifice is bigger than the outlet orifice, as was done by Beasley; although the outlet orifice in his device had a diameter of about 1/7 that of the inlet, he was able to eject droplets of about 70% of the transducer displacement [Beasley, p.82]. In addition, nozzles of different geometries ought to be considered; with ceramic nozzles, for example, it is much easier to view the meniscus motion than it is with the jewel nozzles.

Excess air in the fluid chamber seemed to be a problem, as evidenced by the low velocity, low drop volume streams that were ejected. This is certainly a serious problem and is likely to be chronic: one solution might be to assemble the jetting device under water.

Finally, research should be done on driving these types of DOD devices using discontinuous pulses. The nature of drop-on-demand jetting is that it is possible to generate a drop whenever desired, even if that means waiting relatively long periods between pulses. There are significant start-up problems associated with operating in this "burst" mode instead of the continuous mode, which should be investigated. A jetting device is not truly drop-on-demand unless it can operate reliably in either continuous or burst modes. Taking advantage of the arbitrary waveform generator, it may be possible to solve some of these start-up problems by using special waveforms; more research on input wave characteristics could be extremely useful.

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