Design and Control of Precision Drop-on-demand Herbicide Application in Agricultural Robotics

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***Abstract*—Drop-on-demand weed control is a field of research within Precision Agriculture, where the herbicide application is controlled down to individual droplets. This paper focuses on the fluid dynamics and electronics design of the droplet dispensing. The droplets are formed through an array of nozzles, controlled by two-way solenoid valves.**

A much used control circuit for opening and closing a solenoid valve is a spike and hold circuit, where the solenoid current finally is discharged over a Schottky diode on closing. This paper presents a PWM design, where the discharge is done by reversing the polarity of the voltage. This demands an accurate timing of the reverse spike not to recharge and reopen the valve. The PWM design gives flexibility in choosing the spike and hold voltage arbitrarily, and may use fewer components. Calculations combined with laboratory experiments verify this valve control strategy.

In early flight the stability of the tail, or filament, is described in theory by the Ohnesorge number. In later flight, when a droplet shape has formed, the droplet stability is governed by the Weber number. These two considerations have opposite implications on the desired surface tension of the fluid. The Weber number is more important for longer distances, as the filament satelites normally catch up and join the main droplet in flight.

I. Introduction

In this paper we study the use of a H-bridge, PWM, as the valve control strategy for a drop-on-demand(DOD) herbicide application in precision agricultural robotics. The design and control strategy has been guided by experiments with droplet dynamics, and the effect of reverse voltage overshoot has been illustrated.

Weed control is a vital part of agriculture, and herbicide application is the most efficient and common control strategy. Environmental and health concerns lead to restrictions and regulations on the use of herbicides, which stimulate initiatives for other weed control strategies [1]. Precision agriculture is an active area of research and methods in agriculture which focuses on adapting the field treatment to the spatial and temporal heterogenity of a field. Weed control in row crops, such as carrots, can be seperated into controlling weeds within, and in between the crop rows: Intra- and inter-row weed control.

DOD herbicide application for intra-row weeding has been investigated by several research groups: [2] designed a robotic weed control system for tomatoes, [3] developed an automated detection and control system for volunteer potatoes in sugar beet fields and [4] created a crop/weed discriminating microsprayer. Common for all tree applications is the use of a valve array to only target the weeds, thus avoiding crop and soil. The literature displays promising results, and experiments indicate that the herbicide usage can be reduced by more than 95 % [1]. The literature also illustrates that there are remaining challenges with precisly targeting droplets, classifying weeds by machine vision and maintaining a precise motion estimate for the robotic platform and nozzle array. The review article [5] presents a good overview of the field.

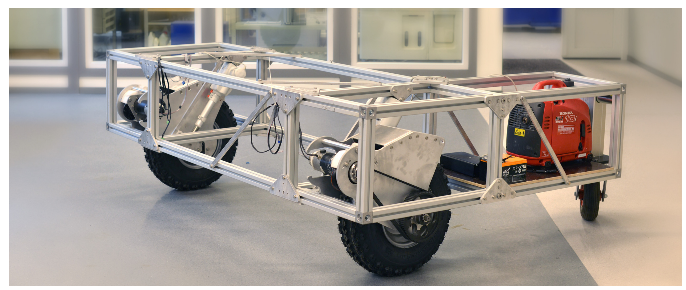


Fig. 1. The Asterix robot platform design for operation in row crops. The platform has two driven wheels and a passive caster wheel. The Asterix modules with the DOD system and machine vision will be mounted in the open area between the two wheels.

The work presented in this paper has been done in the framework of the Asterix project, which works towards a functional robot for DOD intra-weed control in carrots and other row crops. The robotic prototype platform for Asterix is shown in Figure 1 and the localization and attitude estimation for this robot has been described in [6]. In the following sections we will focus on the design and control of the DOD array of nozzles and the control strategy, while we also present our experimental results accompanied with some of the fluid dynamic theory of droplet stability. Droplet stability for at least 15 cm is necessary for this application.

A. Valve and nozzle limitations

The valve and nozzle used are of type INKX0514300A and INZA4710975H respectively, from The Lee Company, as illustrated in Figure 2. The requirement on resolution of control decides what time of the season a system is effective. The control resolution will have a practical lower limit depending

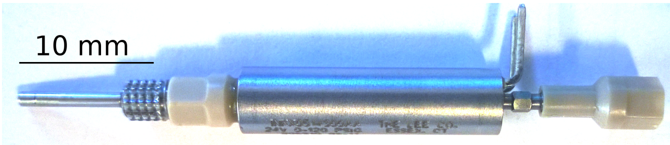


Fig. 2. A VHS valve, INKX0514300A, with minstack mountings and nozzle, INZA4710975H, from The Lee Company.

on the droplet accuracy. If the droplets have an accuracy of ± 2.5 mm there is no need to have finer resolution than 5 mm$\times$5 mm as it would result in many droplets missing the target. The sideways resolution is only a function of nozzle placement, ref. [4] used one row with a spacing of 10.5 mm. Their results and calculations showed that the system was not suitable for targeting weeds smaller than 11 mm$\times$11 mm. Ref. [3] used a similar system with resolution of control about 100 mm^2. Thus neither system will be efficient in the early stages of the season when the weeds are still smaller than 100 mm^2.

The resolution in driving direction can be controlled by the frequency of the valves and the velocity of the vehicle. For instance, ref. [3] used a valve limited to a maximum frequency of 80 Hz, and the demand for control resolution was 100 mm^2, thus limiting the velocity of the vehicle to 0.8 m/s.

Flat fan nozzles are an alternative that allows for smaller weeds to be targeted by spraying a small patch. Recent work has investigated the efficiency of patch spraying with flat fan nozzles [7]. These tests showed promising results for spraying of 100 mm$\times$100 mm patches. When working with row crops, especially carrots, a DOD application with finer resolution is interesting, as the seeds are placed close to each other and weed in between should be controlled. The use of flat fan nozzles in row crops was also examined in ref. [3], where DOD was found beneficial.

Solenoid valves have an upper limit for droplet frequency, and for some microdispensing valves this limit may be hundreds of hertz. However, due to the required droplet volume, the real upper limit may end up around 100 Hz, as a higher frequency would further reduce the volume. Relevant volumes per droplet for a DOD herbicide application lies between 1 μL and 5μ L, and on-times of about 10 ms.

One aspect that needs to be considered when dealing with valve opening time intervals of a few milliseconds, is the fluid dynamics. The fluid in a straight tube can be modelled as an equivalent electrical circuit [8]. This can then be applied to simulate the fluid response in the nozzle under ideal conditions. Increasing the diameter or decreasing the length of the nozzle will result in increased volume rate deposition, but may alter the properties for the droplet in flight.

B. Droplet formation

A droplet produced by a DOD system consists of two or three sections, the main droplet, the filament and a tail. The filament is a cylindrical stream of flow following the main droplet, while the tail is a thin flow behind the filament. The different parts are illustrated in Figure 3. For more information consult [9].

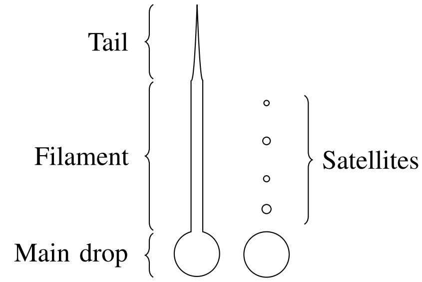


Fig. 3. Droplet definitions

The relative importance to the filament stability from surface friction and viscosity can be expressed through the Ohnesorge number:

$$Oh = \frac{\eta}{\sqrt{\rho \sigma R}} \tag{1}$$

where η, ρ and σ are the viscosity, density and surface tension of the liquid, respectively, while R denotes the radius of the cylindrical filament [10]. Furthermore, the initial filament aspect ratio, $\Lambda = L/2R$, will decide if the filament breaks up or not, L is the length of the filament. The critical value for filament breakup, Λ_c, increases with Oh [10].

When the droplet is falling, a number of scenarios may occur: the filament may be absorbed into the main droplet, it may break at the main droplet thus creating a single satellite droplet or a Rayleigh-Platou instability may occur, creating multiple satellite droplets [9].

Satellite droplets are small droplets lagging behind the main droplet, often caused by the disintegration of the tail or filament. Without wind and other disturbances that could be present for a DOD application in movement, the satellite droplets will typically catch up with the main droplet and coalesce with it, and the dispensed fluid volume reaches the target as a single droplet [11]. An image sequence illustrating this is presented in Figure 8. This is a result of less drag on the satellites as they are smaller and travel in the wake of the main droplet. This will happen under ideal conditions, but how the satellites will behave in the field is not certain. Most of the research described above are results from ink jet printers with droplets much smaller than what is needed for herbicide applications. However, ref. [12] verifies that the theory applies for larger droplets as well, which is more relevant for this project.

The Weber number is of importance when studying the droplets in air, and is defined as, [13]:

$$We = \frac{\rho u^2 d}{\sigma} \tag{2}$$

Where ρ is the density of air, u the droplet velocity, d the droplet diameter and σ the surface tension. With the assumption of spherical droplets, the droplet is stable if its Weber number is below the critical Weber number, which lies between 10 and 40 [14].

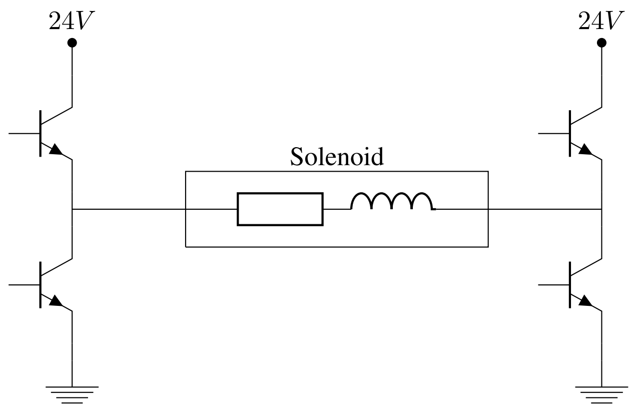


Fig. 4. PWM H-bridge valve driver for a single solenoid

C. Herbicide efficiency with DOD

By far the most common herbicide in use today is glyphosate. It has been widely used through the past 40 years [15], and a water solution of glyphosate is a natural and common choice for DOD weed control [5].

Tests on the efficiency of single droplets of herbicide is presented in [16]. The tests were done with seeds of *Solanum nigrum* planted in pots under outdoor conditions. Results showed that approximately $0.8\,\mu$g of glyphosate per plant reduced the biomass by 95 % when applied by hand.

In field trials with a DOD system, the microspray system was set to dispense droplets of $2.5\,\mu$L with $5\,\mu g$ glyphosate each. The system achieved 82 % efficiency when the average dose per plant was $22.6\,\mu$g. This is only about 4 % of the recommended application [16].

II. Valve Control

In DOD applications the ideal solenoid valve would open and close instantaneously, and the droplet size would be directly proportional with the opening time of the valve. Any physical solenoid valve has a response time τ, which allows for the solenoid coil to charge and the plunger to open. In selecting a valve for DOD applications, one should focus on achieving a response time significantly smaller than the open time, $\tau < T_{open}$.

Several methods are in use for valve control. Typical configurations are: **Single voltage source** controlled by a transistor. This is a simple driver, but it takes longer to open the valve, as the voltage cannot be higher than the hold voltage as it may burn off the coil. Thus charging the coil takes longer than using a higher voltage source. **Spike and hold** drivers with two different voltage sources, one for the spike and another for the hold voltage. They are more complex, but achieve a much faster response. Common for both configurations when closing the valve is that the energy in the coil is burnt off over two diodes in reverse series parallel to the valve. Another solution is to use **PWM** control to create a spike and hold driver equivalent, with diodes to discharge the coil. However, if the PWM is extended to a full H-bridge, it can be used to discharge the energy in the coil.

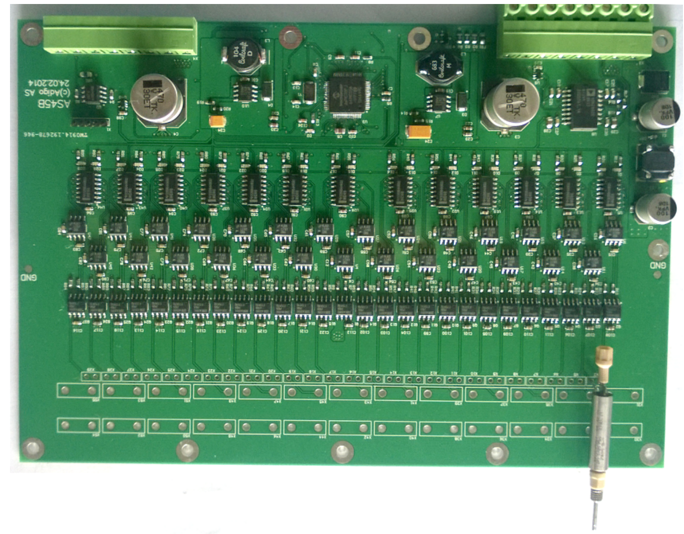


Fig. 5. The DoD demand control unit with one valve and nozzle mounted for an experimental setup.

A. Comparison of PWM and Schottky for solenoid discharge

The main idea for controlling the valve with PWM is that only one voltage source is needed, in a traditional spike and hold driver, two sources are needed, as the spike voltage will overheat the valve if applied for too long. When using PWM the voltage source can be adjusted to fit the spike voltage, that way a large spike followed by a PWM signal to reduce the voltage to the hold value will simulate a spike and hold driver circuit. The PWM control can discharge the solenoid by reversing the voltage over the diode for a significant time, so the current in the coil reaches zero. It is important that the current avoids excessive undershoot as this may open the valve for a short duration before it is closed. This solution will be detailed below. The schematic principle for one single valve driver is presented in Figure 4. When closing the valve, the voltage is reversed over the valve, thus discharging the energy in the coil. The discharge time is reduced with increased voltage, just as the opening time is reduced by increased spike voltage. The Schottky diode solution discharges the coil by burning off the energy in the coil over two schottky diodes in reverse series.

When using the PWM method, the voltage across the valve is limited to the spike voltage, but when using diodes the voltage can be increased further. 50 V reverse voltage is quite common for the schottky diodes for small solenoids with a hold value of about 3.5-4.5 V. The time to close the valve with an internal resistance of 40 Ω, inductance of 12 mH, and hold voltage of 4 V can be calculated for the different solutions. The current response of a resistor in series with an inductor follows the first order response:

$$I(t) = I_0 + (I_1 - I_0)(1 - e^{-t/\tau}) \tag{3}$$

where $I(t)$ is the current at time t, I_0 is the initial current, I_1 is the steady state current for the final solution and τ is

TABLE I
ELECTRICAL CHARACTERISTICS FOR THE LEE INKX0514300A VALVE FROM DATASHEET

Description	Value
Resistance	40 Ω
Inductance	12 mH
Hold voltage	4 V

TABLE II
EXPERIMENTAL AND CALCULATED REVERSE VOLTAGE SPIKE TIMES, WHERE THE FINAL CURRENT IS THE EXPECTED OVERSHOOT OR RESIDUE CURRENT IN THE SOLENOID COIL.

Description	Negative spike duration (ms)		Final current
	Theoretical	Experimental	(mA)
Scottky	0.0231	-	0
Ideal PWM 24V	0.0463	0.05	-8.31
Control PWM 24V	-	0.10	-99.15

the time constant. For the PWM solution with 24 V the time to reduce the current level to zero is 0.0463 ms while using 50 V diodes results in a time of 0.0231 ms. This is about half the time, but represent a very small portion of the time which the valve is open. A typical open time interval for the solenoid is $T_{open} = 8$ ms. The response time of the valve is about $\tau \approx 0.3$ ms. The effect on the tail will be examined by experiments to ascertain whether this control strategy works or not.

The complexity of the control configurations is another aspect that needs to be inspected. For a microdosing system it is important to have a fast response circuit as a spike and hold circuit. There are many solutions for such a driver, but the main difference discussed here is how to discharge the energy in the coil. Regardless of the solution chosen the PWM approach will result in fewer components than the schottky diode solution for a valve matrix. This is achieved by using a half H-bridge for all the valves, in addition to a half H-bridge that is common for all valves. That way two diodes for each valve is avoided and only two more transistors are needed. This makes the circuit less complex and easier to control.

Another advantage for the PWM control is the need of just one voltage source. A solution to remove one voltage source for the spike and hold driver is to use a voltage regulator to produce the hold voltage. The problem here is that when the number of valves increases, several regulators are needed as the current becomes larger. The reduction in components influences the cost of the final PCB as well. Another significant advantage is that the PWM solution is more flexible. If the valve is replaced, the only requirement for the new valve is that the spike voltage needed does not exceed the initial design specifications. Thus only software adjustment is required instead of modifying the circuit.

B. Negative spike time

The negative spike time of the PWM circuit must be carefully chosen. The electrical characteristics of the valve are

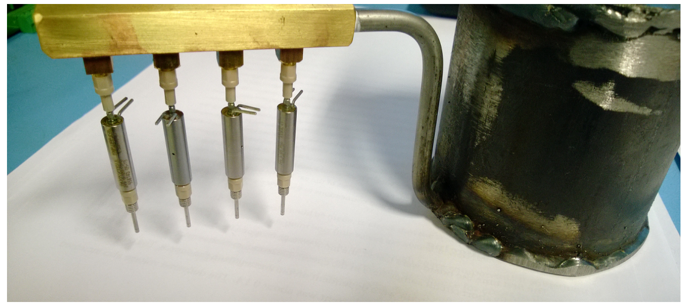


Fig. 7. Experimental setup with valves and pressurized liquid container, for early experiments with droplet formation, as shown in Figure 6 and 8.

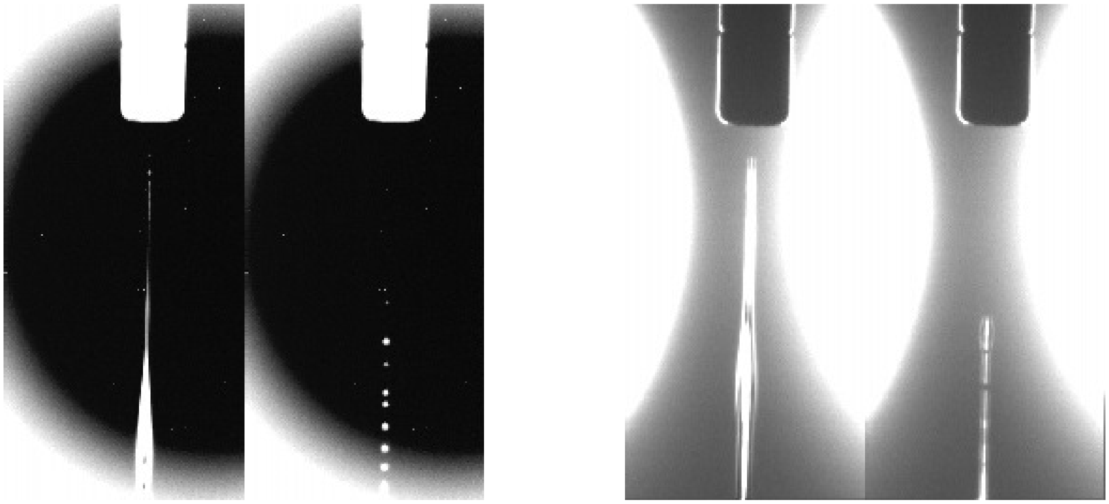
presented in Table I. Using the first order response of the RL circuit as in Equation 3 the exact time can be derived. The timing and currents are presented in Table II. As calculated before the time for closing the valve under ideal conditions is 0.0463 ms. In practice the resolution in time may have to be limited. The important part is to have the current close to zero so the plunger is not activated again. The residue current will be burnt off over the diodes in the transistors.

To test how the closing time influences the droplet, a test rig was set up. This was done with a black and white high speed camera, PROMON 501 from AOS Technolohies. To provide sufficient light for shooting with 1000 fps a LED panel was placed behind the nozzle pointing directly at the camera. The valve was operated by the PCB controlled from a computer. The rest of the setup consisted of a pressurized liquid container with water and tubing, as shown in Figure 7. The pressure was set to 0.4 bar, which produces droplets with an initial velocity of about 4 m/s. In this experiment regular tap water was used.

The main test was to see how the time resolution affected the droplet, initially two spike times were chosen. The requirement was that both times should be realistic regarding how the system will be programmed for the field. For the first test the spike duration was set to 0.1 ms, while for the second test it was 0.05 ms. The calculations represented in Table II shows the theoretical times for discharging the energy in the coil and the theoretical residue current for the experimental times. A spike duration of 0.1 ms should result in a current of -99.15 mA, while 0.05 ms result in an undershoot of -8.31 mA. A current larger than 87.5 mA is enough to hold the valve open. Thus the larger spike duration may cause the valve to start opening again. In this test it was of interest to see how such an undershoot affects the droplets properties. An undershoot of -8.31 mA should not be enough to actuate the valve at all, thus the difference should be observable.

C. Results

The experimental setup was designed with one valve with a pressure of 0.4 bar. The spike voltage was set to 24 V and the hold voltage to 3.96 V. The only difference in the two tests was the negative spike duration. Figure 6a shows the end of the droplet using a spike duration of 0.1 ms, while Figure 6b shows the end of the droplet when using 0.05 ms for the spike duration. For the first test a thin secondary tail is observable



(a) Test 1, tail, $U_{hold} = 3.96\,\mathrm{V}$, $t_{spike} = 0.1\,\mathrm{ms}$

(b) Test 2, tail, $U_{hold} = 3.96\,\mathrm{V}$, $t_{spike} = 0.05\,\mathrm{ms}$

Fig. 6. High speed footage of the droplet tail with a pressure of 0.4 bar, 1000 fps. Figure (a) show the extra tail resulting from the reverse spike overshoot.

before it breaks into many small satellite droplets. This is however avoided in the second test. Common for both tests is that the filament is beginning to break up. The length of the filament makes it unstable as described previously. The breakup of the tail in Figure 6a is similar to filament breakup, but because it is so much thinner than the filament it breaks up faster and to smaller droplets.

Under ideal conditions the satellite droplets will overtake the main droplet, but in practice, the robot will be moving and the presence of wind may affect the satellites differently than the main droplet. Thus the filament breakup and the tail breakup should minimized. This is to reduce the possibility of satellite droplets not merging with the main droplet and missing the target.

III. Discussion

For the autonomous weed control application to work, the DOD system must be very accurate. The accuracy does not solely depend on target precision, but the presence of satellite droplets and their behavior. It is crucial that the satellites coalesce with the main droplet, or that they both hit the same spot. Therefore the droplets tail should be minimized, as the tail will split up in much smaller droplets than the filament.

The usual method for driving solenoid valves in this kind of a application is by a spike and hold driver circuit, with two diodes in reverse series to discharge the energy in the coil. However the described method is based on a full H-bridge, for PWM control. The maximum voltage is chosen as the spike voltage, thus a long spike will open the valve before the PWM control limits the voltage to the hold value. When closing the valve the energy in the coil is discharged with a significant negative spike. The spike time has been calculated using the first order response of a RL-circuit when the inductance and resistance of the valve is known.

Tests of how this control strategy performs confirms the theory, as a long spike time resulted in a thin secondary tail,

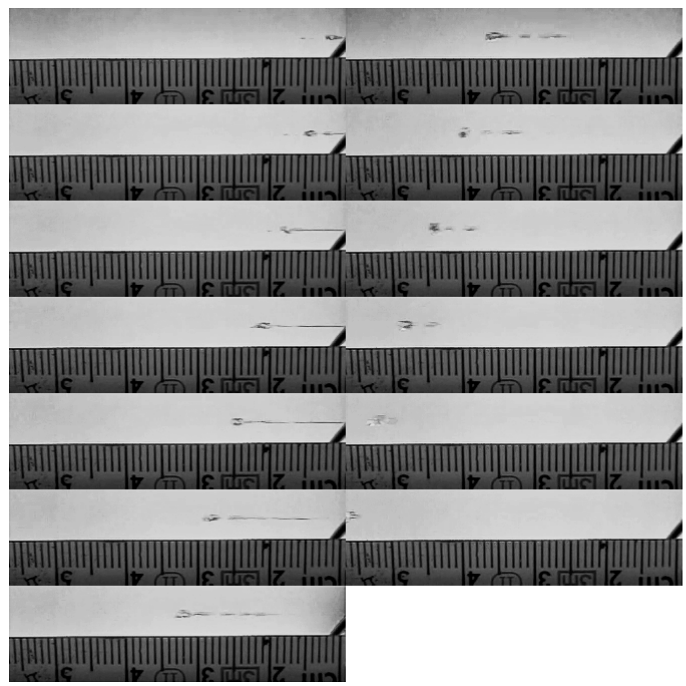


Fig. 8. 1200 fps image sequence of a water droplet with initial velocity of 4 m/s (illustration taken from ref. [17]). The filament first break up to satellites, which then drift in the wake of the main droplet, and join the droplet.

while a spike time of appropriate length avoided this. The long spike time started to actuate the plunger when it should be closed, but the small undershoot for the appropriate time did not actuate the plunger at all.

Thus the spike time of 0.05 ms is close enough to the theoretical time for closing the valve. A possible solution for decreasing the filament break up in this application is to use a larger nozzle and shorter on-time. That way the circumference-to-length ratio is increased for droplets with the same volume. The time before the filament breaks up is thus increased, and the filament will break up in larger and fewer droplets. Manipulation of the liquid to increase the Ohnesorge number is another solution for decreasing filament breakup. However, this is likely to influence the Weber number and stability of the droplet.

The main disadvantage of PWM control is the increase in time for discharging the energy, as the diodes can be chosen with a higher voltage level. This is not as easy with the PWM solution, as the higher the voltage, the more robust the components must be. This is due to the increase in voltage when using only one source will influence the robustness of the components, especially the transistors, used in the PWM control.

However there have not been observed any significant negative effects of the slower closing of the PWM solution compared to the Schottky closing. Thus an increase in the voltage is not necessary.

Breakup of the filament was observed in the tests, but this will occur regardless of the control strategy, and might be decreased with increased nozzle diameter. The theory and calculations regarding the valve control was confirmed by the experimental setup. The tail was avoided although the closing time is increased compared to the diode solution, thus the advantages of the PWM control strategy may be exploited. This includes a more flexible design with regards to the valves and fewer components are needed for the circuit. The main focus is to make sure that the negative spike time does not undershoot too much as this will create a tail that should be minimized.

Theory regarding the Ohnesorge number and filament breakup finds that a liquid with low surface tension and high viscosity reduces the filament breakup as the Ohnesorge number increases. However when the droplets have to travel a significant distance before hitting their targets it is important that the droplets do not disintegrate. The increased stability of the droplet leads to more satellites due to increased filament breakup. Under ideal conditions the satellites from filament breakup will merge with the main droplet, but this may not be the case in the field. Clearly the best solution would be to avoid filament breakup while maintaining a stable droplet in air. A compromise between the Ohnesorge number and the Weber number is of importance when shooting droplets a significant distance. This is due to the requirement of a stable droplet throughout the whole flight, while trying to minimize the filament breakup.

IV. Conclusion

A valve controller has been developed for drop on demand weed control, using a full H-bridge design and PWM voltage regulation to generate the spike and hold voltages. In contrast with common design practices with solenoid drives, we have not included the discharge diodes. The solenoid discharge is instead done by applying a reverse voltage to the solenoid.

The timing of the reverse voltage has to be calculated using the solenoid inductance given from the datasheet. If the reverse spike is held longer the solenoid may reopen and dispense a secondary tail, which will create additional satellite droplets. If the reverse spike is not long enough the residue current will discharge over the protective diodes in the H-bridge drivers.

The design results in fewer components per solenoid, but demands accurate timing of the reverse voltage spike. The PWM allows for arbitrary spike and hold voltages up to the supply voltage, which for this project has been 24 V. The experiments also illustrate the filament breakup and its connection with the Ohnesorge number, while the Weber number is essential to the stability of droplets in flight.

Acknowledgment

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