Satellites occurrence and approaches to eliminate them

Introduction

The typical electrical pulse applied to the piezoelectric actuator is a trapezoidal waveform (positive only or positive followed by a negative) as shown in Figure 1. The transitions from one voltage level to the other reduce/increase the cross-section of the tube capillary and produce pressure variations (with respect to resting conditions) of the fluid enclosed in the tube. Ramps from low to high voltage levels produce an expansion of the cross-section resulting in a lower pressure. During "rise time" the inner surface of the glass tube moves outward and a negative pressure (expansion) wave is generated and starts to move both towards the supply and the orifice ends. At the supply end the wave reflects as a positive pressure (compression) wave. The "dwell time" (time at the high voltage when the structure does not move) is selected such that the "fall" of the drive signal starts when the reflected positive pressure wave reaches the middle of the channel. The voltage "fall" corresponds to a compression of the fluid (inward motion) and thus reinforces the reflected wave for a minimization of the required voltage or maximization of the drop velocity at the same applied voltage. When the reinforced compression wave reaches the orifice, the acoustic energy is converted into kinetic energy due to the impedance mismatch (constant pressure boundary condition), which causes the fluid to start emerging from the orifice at high velocity. When a negative pressure wave reaches the orifice the fluid starts to pull back and the emerged fluid forms in a drop (or a drop followed by satellites).

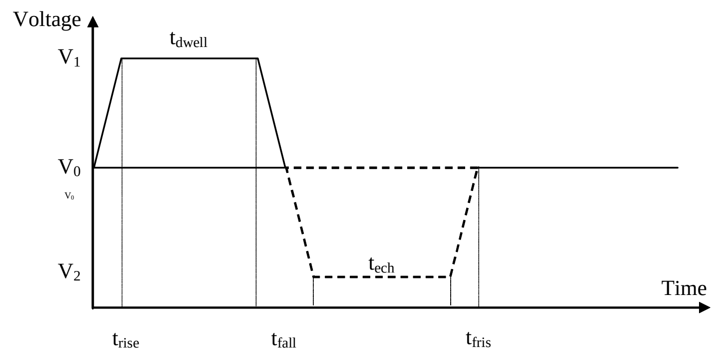

Figure 1. Electrical signal applied to the piezoelectric actuator.

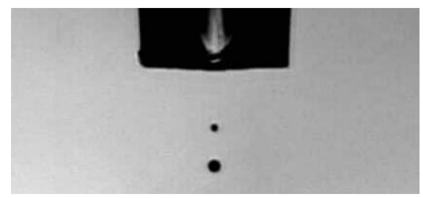

Figure 2. Drops of polymer dissolved in isobutanol at 240Hz. The larger drop is the main drop and the smaller drop is the satellite.

The negative part of the waveform ("echo") will be discussed as a method to eliminate satellites.

Satellites form through a combination of the properties of the dispensed solution and the driving waveform. Some of the possible causes for satellites are:

1. Some viscoelastic fluids produce a very long and thin tail behind the main drop. This tail typically breaks down in a small cloud of fine satellites (Figure 3) that trails the main drop. Solutions of high molecular weight polymers can exhibit this type of behavior.
2. For low surface tension fluids, the ejected fluid has an elongated appearance. The end of the fluid

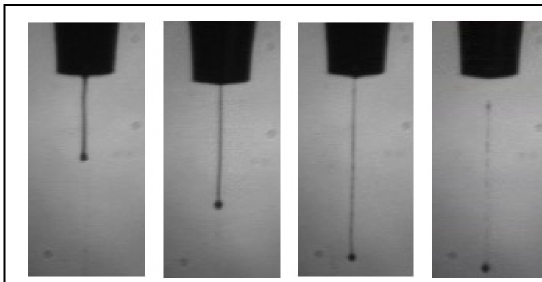

Figure 3. Drop formation characteristic of viscoelastic fluid (5% polystyrene in aromatic solvents).

ejected from the orifice is often broken off from the beginning resulting in a main drop and a large trailing satellite (Figure 4).

3. For some fluids of low viscosity the pressure waves that still travel in the device after the formation of the main drop could still have enough energy to eject fluid that forms satellites. Typically this would be a lower velocity satellite (if the voltage is within reasonable limits).
4. If the applied voltage is too high the ejected volume is larger and it will be broken down into the main drops and several satellites. An indication of the voltage range is the velocity of the main drop, which should be 2-3 m/s. The velocity can be determined by calibrating the reticule on the screen and measuring the time it takes the drop to move over a known distance. This time can be determined by changing the strobe delay.

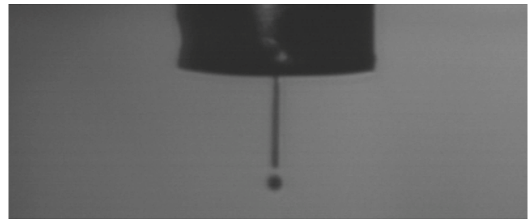

Figure 4. Dispensing of isopropyl alcohol (22 centipoise surface tension). Necking down occurs behind the front end of the ejected fluid with the fluid between that point and the orifice becoming a large satellite.

<u>Comments</u>

Satellite free dispensing is not required in all applications. If dispensing (single or multiple drops) in print on position mode is required, the presence of satellites is not an issue as long as they are consistent and follow the trajectory of the main drop. The only aspect to be considered is that the volume per "event" consists of the volume of the main drop and the volume of the satellite.

As the fluid plays a significant role in the satellite formation, there is no general recipe to eliminate the satellite. The approach is to identify the possible cause of the satellites and then use the adjustments described above while observing the changes that are produced in the drop formation.

<u>Available adjustments</u>

Solution changes

In some cases it is possible to adjust the dispensed solution. This approach can be made to make jetting easier and, at the same time, to eliminate satellites. The optimum properties for ink are: 30-50 dyne/cm surface tension; 4-8 cetipoise viscosity (assuming Newtonian behavior). Droplets can be generated in wider windows for these properties, but it is easier to achieve good operation for the range described.

The non-Newtonian behavior shown in Figure 3 can be diminished or eliminated by changing the solution's solvents or reducing the concentration of the polymeric materials. The low viscosity solutions could have their viscosity increased by additives.

Voltage adjustment

The drop velocity increases with the voltage at constant timings. If the voltage is too high it could result in residual waves that have enough amplitude to eject other drops (satellites) besides the main drop.

In most cases, the high voltage is the primary cause for satellites. Reducing the voltage in increments of 2-5 V might reduce or completely eliminate the satellites. While reducing the amplitude of the voltage, measure the main drop velocity. The desired drop velocity is in the range 1.5-3 m/s (water has a tendency of creating satellites starting at 2 m/s). The drop velocity measurement is done by determining how long it takes the drop to travel a certain distance on the video screen. It requires the screen to be calibrated at the magnification used. The travel time is obtained by adjusting the strobe delay such that the drop appears on the screen at the end point of the travel. The velocity is calculated as distance over time.

The voltage should be reduced until the drop velocity is in range and no (or a single) satellite is present. Adjust the voltage in 1 V increments when getting close to this type of condition. If the satellites are eliminated, the process is complete. If one satellite still occurs, explore other methods described below.

When getting to a single satellite two situations can be encountered: slow satellite (the satellite is close to the orifice and it has low velocity which is typically shown by wandering trajectory and being far behind the main drop) or fast satellite (close to the main drop and typically following a straight trajectory). The slow satellites can be addressed by further reducing the voltage, which will reduce the energy of the residual waves to a level insufficient to create the satellites. For the high velocity satellites, the voltage should be increased in an attempt to merge the satellite with the main drop.

Timing adjustment

When actuating the micro-dispenser using only the positive part of the trapezoidal waveform and at constant voltage and rise and fall times, the drop velocity (as a function of the "dwell time") has a shape of concave parabola with a maximum around $2L/c$ (L- distance from the center of the PZT to the supply end of the device; c- effective speed of sound in the device; usually slightly smaller than the speed of sound in the infinite fluid because of tube compliance) - Figure 5. The length L depends on the actual device configuration (11.5-12.5mm). The maximum in velocity is produced because the compression caused by the fall (at the end of the "dwell time") coincides with and reinforces the reflected (positive) pressure wave from the supply connection.

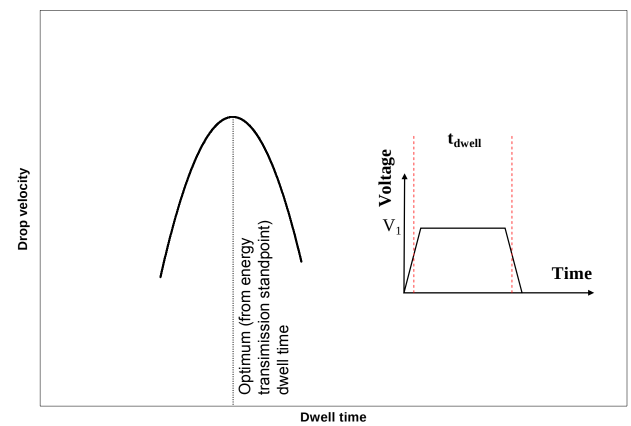

Figure 5. Measurement of "dwell time" and the effect of it on drop velocity.

By changing the "dwell time" the pressure increased by fall at the end of the "dwell time" is mismatched with the pressure wave reflected from the orifice and thus it increases the length of time at which positive pressure is present at the orifice. The droplets are slower as we move away from the maximum and it is possible to use this to eliminate the satellite. The short pulses could also be used to create drop size modulation (changing the drop diameter).

Note: The drive electronics limit the rise and fall times such that the ramps are less than 50V/µs. For the purpose of this approach, the actual "dwell time" has to be measured between the middles of the rise and fall times. For this reason, increasing the "rise time" and "fall time" will have an equivalent effect of increasing the "dwell time".

The use of the echo (negative) pulse

The echo pulse is used to cancel the residual acoustic waves propagating in the tube. The timing is selected such that the piezoelectric expansion corresponds to a positive (compression) pressure wave, which is about twice the “dwell time” (if the optimum dwell time – maximum velocity – is selected). The fine tune can be done keeping all the parameters the same and adjusting the “echo pulse” in 1-2 μs increments while observing the drop formation. Adjust the delay (strobe or software) such that the image shown on the screen shows the moment of satellite break-off. The goal of the adjustment is to cause the satellite to no longer break-off from the orifice. Usually when the satellite no longer breaks off a fluid excursion is still observed coming out of the orifice and then being pulled back in as the negative pressure reaches the orifice. Continue to adjust the “echo dwell” to reduce the fluid excursion (the distance between the end of the fluid and the orifice face).

This approach has the best results if the satellite is produced by the residual waveforms (a second acoustic reflection reaching the orifice), which typically translates in a slow satellite.

Vacuum adjustment

Slow satellites can be eliminated by an increase of the vacuum applied to set the meniscus position flush with the orifice face. Fast satellites might be forced to merge with the main drop if vacuum is reduced (backpressure is increased towards atmospheric conditions).

The vacuum has to be changed only slightly from the starting conditions otherwise it could result in the meniscus withdrawing from the orifice face or fluid dripping out at start-up after idling.