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An Experimental Study to Control Single Droplet by Actuating Waveform with Preliminary and Suppressing Vibration

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Abstract**—**For advancing the experiment system standard of Inkjet printer that is being developed, the actual natural period, fire limitation number in droplet weight measurement and observation distance in droplet velocity measurement was investigated. In another side, the study to control the droplet volume in inkjet printer with negative actuating waveform method is still limited. Therefore, the effect of negative waveform with preliminary and suppressing vibration addition on the droplet formation process, droplet shape, volume and velocity were evaluated. The different voltage and print-head temperature were exerted to obtain the optimum preliminary and suppressing vibration. The mechanism of different phenomenon from each waveform was also discussed.

Keywords**—**Inkjet printer, DoD, waveform, preliminary and suppressing vibration.

I. Introduction

RESEARCH development in inkjet printing experiment system is being carried out to increase the inkjet printer performance and its printing result. This study is devoted to some of the most important issues for advancing inkjet printing experiment system with a focus on piezoelectric droplet on demand (DOD) inkjet technology. A good understanding of the drop formation process is important for improving the print quality of inkjet systems. The inkjet micro droplets experimental investigation is challenging, because of tiny drop sizes and high speeds of droplets [1]-[3].

It is important to establish a good experiment system and build the design of experiment to reach an effective and efficient experiment system. To ensure the experiment result and analysis particularly in finding the best waveform design, it is important to build the experiment standard. This joint research with inkjet printer's company aims to propose the fire limitation number for droplet weight measurement and distance from nozzle head for velocity measurement on inkjet printer experiment system standard. Mostly, 1.000.000 drops were used in droplet weight measurement, and it needs more than 20 minutes to gather 1 data. In another side, there is no standardization in droplet distance observation in droplet velocity measurement. Therefore, in this study, we evaluate the experiment system and decide the experiment system standard. The other objective of this study is to determine the actual natural period of inkjet printer. The computation of time parameters of the actuation pulse can be simplified if the natural period is known [2]. In addition, by knowing the waveform that generates the highest droplet speed, we can determine the most efficient parameter to drive printer-head [9]. Therefore, the actual natural period from this experiment result is used as a recommendation to the company for generating the higher speed of droplet.

The droplet ejection process, shape, volume and velocity are influenced by actuating waveform of the piezoelectric element [2], [4], [10]. Some studies were conducted to investigate the droplet behavior [1]-[14], [18], [23]. Most of the studies were using positive (trapezoidal) waveform or positive and negative (bipolar) waveform [3], [5], [6], [10], [16], [17], [19]-[22]. Kwon et al. proposed the method of designing an efficient waveform. In this study, three different types of waveform using positive (trapezoidal) waveform as a basic waveform, high-speed jetting waveform using positive and negative (bipolar) waveform, and negative waveform, were compared and designed to determine the optimal value of dwell time [6]. Kim et al. used double piezo-actuators with bipolar waveform and investigated its effect to ejected droplet speed [8].

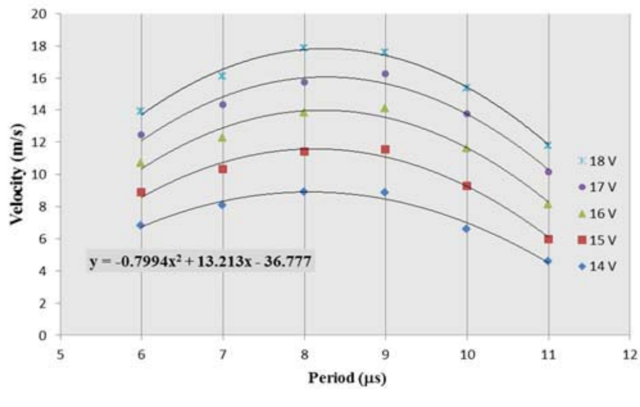

Fig. 1 Droplet velocity as T_{keep} function

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Shin et al. used double positive waveform to observe its effect to droplet formation and stated that the simplest waveform for driving the piezoelectric actuator to generate a droplet is unipolar waveform and the study that using negative waveform is still limited [7]. Hence, we used the unipolar negative waveform for piezoelectric (PZT) print-head as the actuator to eject the droplet.

The applied voltage effect to the droplet speed was discussed by some studies [7], [9], [10], [15], [18], [28], [29]. Xu et al. stated that the higher applied will reduce the droplet size [10], whereas the other studies concluded that the higher voltage will generate the larger size of droplet. In this study, we investigated the effect of different applied voltage in the actuating waveform design with preliminary and suppressing vibration and determine the optimum voltage. The comparison of actuating waveform design with preliminary and suppressing vibration to basic waveform was discussed in details. Dowanol was used as operating liquid and tested by different nozzle head temperature and applied voltage from 14 V until 18 V. By observing the droplet shape, volume and velocity, the optimum base voltage for each actuating waveform could be determined and proposed.

II. Study on Actual Natural Period

Natural period is the time in which a freely oscillating system completes one cycle of oscillation. In inkjet system, the period from the actuator for eject the droplet is at which the droplet reaches the highest speed. The specification of previous period for the actuation parameters are 8 μs with input parameter of waveform; time for down, keep, and up is respectively 2 μs. Hereafter, this period referred as natural period (T_{an}). The objective of this section is to determine the actual natural period of basic waveform for the inkjet device used in this study. The actual natural period is determined from the input parameter of t_{keep} that can give the highest value of drop speed [30]. Therefore, for determining the relationship between t_{keep} and drop speed, the others input parameter was set as fixed value. The input parameter of waveform is shown in Table I. In this experiment, we used 28 °C as head temperature.

TABLE I
INPUT PARAMETER FOR ACTUAL NATURAL PERIOD EXPERIMENT

No	Time (down) → t_d(μs)	Time (Keep) → t_k (μs)	Time (Up) → t_u (μs)	Total Period (μs)
1	1	2	1	6
2	1	2.5	1	7
3	1	3	1	8
4	1	3.5	1	9
5	1	4	1	10
6	1	4.5	1	11

The experiment result for input parameter in Table I is shown in Fig. 1. We can see that the data for droplet velocity with different period formed the quadratic function. From the pattern of experimental curve, the maximum value is in the vicinity of period 8 μs and 9 μs. In other words, parameter value for t_d, t_k, t_u, t_w should be more than 2 μs. In order to determine the exact value of natural period, the quadratic function $y = ax^2 + bx + c$ is used to obtained the maximum number of x, which represents the actual natural period. From that equation, we can determine the estimated actual natural period from maximum value of axis, with (1) and (2).

$$x = \frac{-b \pm \sqrt{b^2-4ac}}{2a} \quad (1)$$

$$x\ max = \frac{-b}{2a} \quad (2)$$

The quadratic function obtained from experimental data is:

$$y = -0.7994x^2 + 13.213\ x - 36.777$$

When a = -0.7994 and b = 13.213 Then $x\ max = \frac{-13.213}{2(-0.7994)} = 8.264\ \mu s$. It is determined that the estimated actual natural period of the inkjet device is 8.2643 μs. Hereafter; this actual natural period is symbolized by T_{an}. From this result, we can propose 8.26 μs as the natural period and 2.066 μs as input parameter of t_d, t_k, t_u, t_w in the inkjet printer device to obtain the higher droplet velocity with basic waveform.

By using actual natural period from this study, the experiment result will be more suitable with waveform concept design, and new standard in inkjet printer experiment system will increase work efficiency.

III. Experiment Standard of Fire Limitation Number

The purpose of this experiment is to determine the correlation between amounts of fire limitation with droplet weight. The null hypothesis is, the difference fire limitation number of droplet do not show the different droplet weight. The input parameter was using basic waveform that shown in Table II.

TABLE II
INPUT PARAMETER FOR FIRE LIMITATION NUMBER EXPERIMENT

t_k	t_d	t_u	Voltage	Fire Frequency	Head Temperature
2	2	2	14V – 18V	1 kHz	27°C

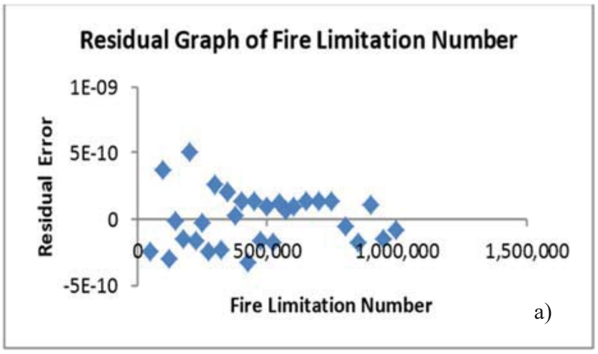
The fire imitation numbers were starting from 50.000 until 1.000.000 (interval 25.000). The hypothesis testing was done by using regression analysis with the results shown in Fig. 2.

Figs. 2 (a) and (c) present the regression result of droplet weight with different fire limitation number. We can see that the R square (R^2) value for that experiment is very small. R^2 = 0.0034 means that the percentage of droplet weight movement is only 0.34% caused by fire limitation number. Furthermore, we can see that the result of significant F value was 0.76093766, more than 0.05. It means that input was not significant to output. In other words, we can say that there is no significant effect of using the different number of fire limitation with the droplet weight. If we compare the time needed for 100.000 with 1.000.000 fire limitation, there was a significant difference of it. It needs over than 20 minutes to take one data of droplet weight for 1.000.000 fire limitation number whereas only ± 1 minute for 100.000 drops.

In addition, the evaporated droplets during firing process could be more when using 1 million of fire limitation number. The partial evaporation of the droplet during their travel from the nozzle may influence the mass measurement [31]. Even though the evaporation effect cannot be neglected [32], however, by using 100.000 drops, the evaporation effect during firing process could be reduced. Hence, it is recommended for using 100.000 drops of fire limitation number for droplet weight measurement standard.

Analysis Result

Regression statistics	
Multiple correlation R	0.057964427
R square R2	0.003359875
Adjusted R square R2	-0.032234415
Standard Error	2.06989E-10
Observations	30

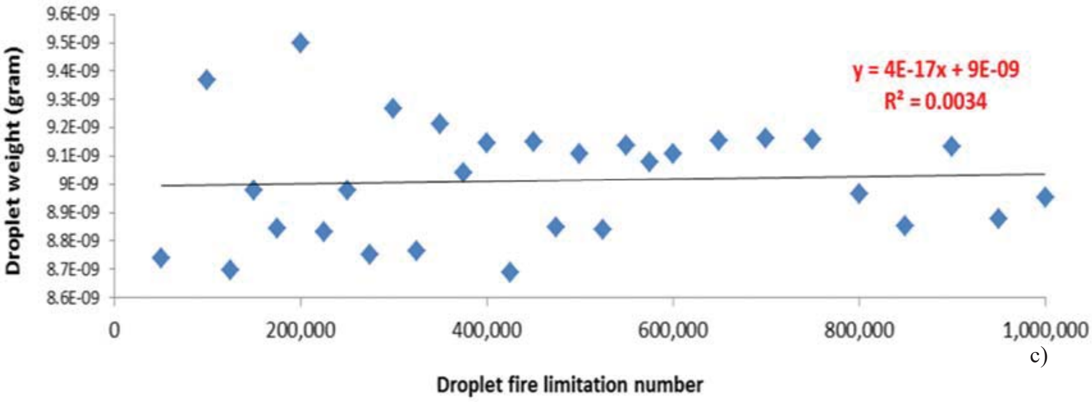


a)

Analysis of variance table

	df	*SS*	*MS*	*F*	*significant F*
Regression	1	4.04425E-21	4.04425E-21	0.094393644	0.76093766
Residual	28	1.19965E-18	4.28445E-20		
Total	29	1.20369E-18			

b)



c)

Fig. 2 Regression result of fire limitation number experiment

IV. Effect of Actuating Waveform to Droplet Formation Process and Shape

A. Actuating Waveform

In this study, we used three negative waveforms as follows;

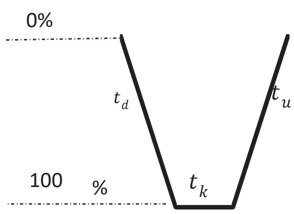
1. Basic Waveform

According to experiment about actual natural period, the recommended input parameter of t_d, t_k, t_u is 2.066 μs. To make it easily to understand, we abbreviated it become 2 μs as basic waveform.

2. Preliminary Vibration

The preliminary vibration serves to accelerate the droplet velocity and increase the volume with one pulse addition in front of the main pulse. The additional front pulse as a preliminary vibration such as the main pulse was using basic waveform but with a different voltage.

Prior experiment was conducted to determine the voltage percentage of first pulse to ensure that the vibration will not cause the droplet ejection to generate the single droplet. This experiment used the different base voltage start from 10% of base voltage until the droplet is really dripped from the nozzle. The input parameters of t_d, t_k, t_u are equal to basic waveform.



$$t_d = t_k = t_u = \frac{T_{an}}{4} \approx 2$$

Fig. 3 Profile of Basic Waveform

The percentage of base voltage with droplet totally ejection (until totally breakup or dripped) is shown in Table III.

The maximum applied voltage of preliminary vibration must be less than 9.9V for no droplet ejection. Therefore, we used 30%-50% of 14-18V as the preliminary vibration voltage. The profile of actuation waveform with preliminary vibration is shown in Fig. 5.

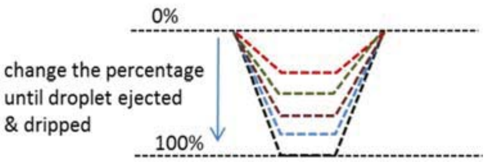
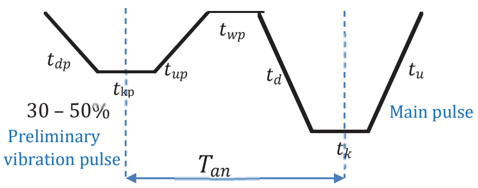


Fig. 4 Prior experiment to determine preliminary vibration percentage

TABLE III
PERCENTAGE OF BASE VOLTAGE (UNTIL BREAK UP DROPLET)

Base Voltage (Volt)	Start ejecting at (% of base voltage)
10	100
11	90.9
12	83.33
13	76.92
14	71.5
15	66.67
16	62.5
17	58.82
18	55.55



$$t_{dp} = t_{kp} = t_{up} = t_{wp} = t_d = t_k = t_u = \frac{T_{an}}{4} \approx 2$$

Fig. 5 Profile of waveform with preliminary vibration

The effect of different voltage percentage from base voltage was investigated to determine the optimum waveform with preliminary vibration.

3. Suppressing Vibration

The suppressing vibration function is to reduce the residual vibration and suppressing the droplet speed and volume. Suppressing vibration in this experiment is applied by the addition of pulse after main pulse. The profile of two kinds of suppressing vibration is shown in Fig. 6. Fig 6 (a) presents the waveform from two same pulses with separating time (t_{keep} 6μs). Fig 6 (b) depicts the waveform from two pluses with different time. The waveform was modified to make it easier to input in the experiment device.

The second pulse for suppressing vibration used half period of actual natural period (T_{an} /2). For the actuating waveform with Suppress B, we used 30%, 40% and 50% of base voltage.

B. Droplet Formation Process, Shape and Velocity on Each Stage

The objective of this section is for investigating the droplet formation process and observing the droplet shape and velocity at different distance from the print-head nozzle. The other purpose is to decide the experiment standard for the droplet observation distance from the nozzle to measure the droplet velocity. Currently, the experiment applies 500 µm as setting distance. In this experiment, we observed the droplet shape and velocity at the different distance from nozzle head, start from 200 µm until 1000 µm. The different voltage was also applied in the experiment, respectively.

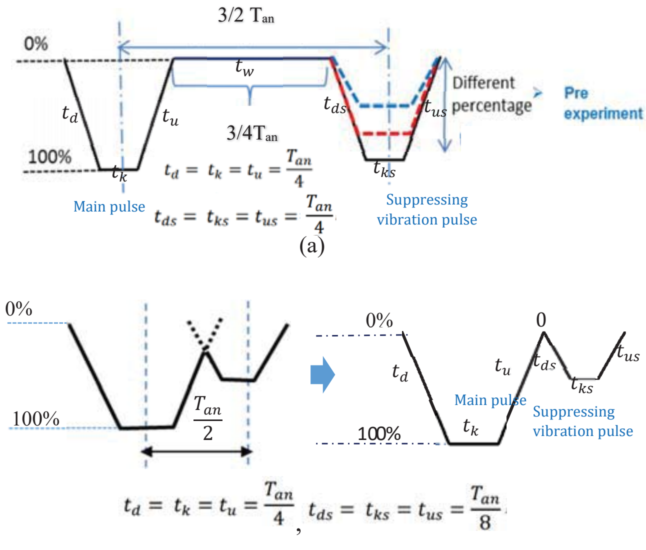


Fig. 6 Profile of waveform with suppressing vibration (a) Suppress A (b) Suppress B

The droplet formation process from the experiment result is shown in Fig. 7. A study that discussed about drop formation divided the process into 4 phases [14]. In this study, we divided the droplet formation process into 3 stages. First stage is when the droplet still connected to the nozzle, at 200 µm for base voltage 14V and 200-400 µm for 15-18V. At this stage, the droplet velocity is still affected by the actuating waveform and generated the higher droplet velocity.

The next stage is when the droplet had breakup from the nozzle and still in a shrinking process of ligament or in the necking process. The velocity at this stage is gradually decreased because of air resistance and there is no pressure effect anymore from the actuator. The third stage if the droplet velocity became more stable, forming the single clear droplet or split off. Two conditions of the droplet when it cannot become a single clear droplet are; the droplet with tail so called ligament, or the main droplet that followed by smaller drop so called satellite. Those two conditions are not recommended for high print quality.

The 1000 µm is recommended for the distance of droplet observation from the nozzle and as standard distance in inkjet printer experiment system for velocity measurement. The other reason, this distance is also the distance standard of printing surface from the nozzle head. With the same distance, the droplet shape in our experiment is equal to the droplet shape when reach the print surface. The drop speed is obtained from the average of distance (D) from nozzle divided by elapsed time between the nozzle head until reaching D (T), appropriate to approach 2 in droplet speed measurement [13]. The droplet speed measurement method is shown in Fig. 8.

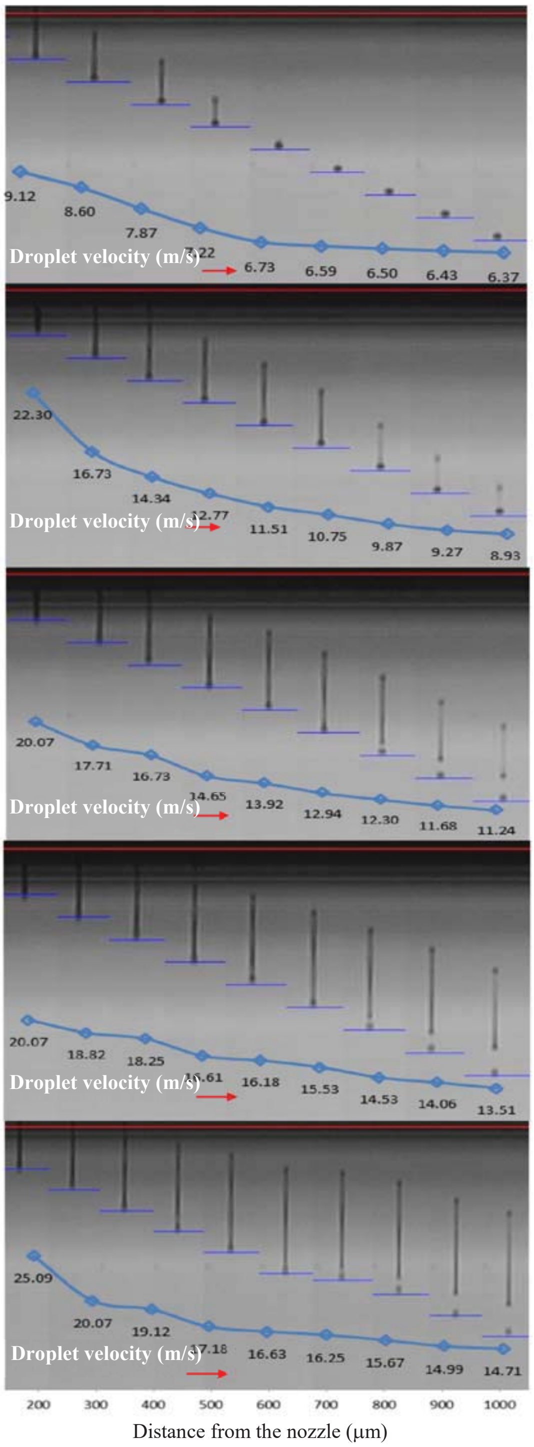


Fig. 7 Droplet formation process and velocity (Basic waveform)

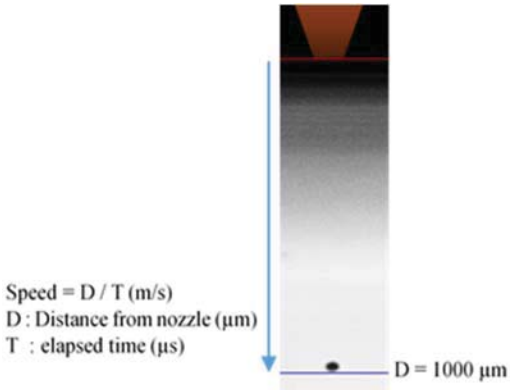


Fig. 8 Droplet speed measurement

The final droplet shape (at 1000 μm from the nozzle) for the basic actuation waveform is shown in Fig. 9. The experiment result for actuation waveform with preliminary and suppressing vibration is shown in Fig. 10. In basic waveform, it is shown that the clear droplet is generated from applied voltage 14V only, whereas over than 14V generates the ligament. The larger voltage caused the longer ligament. This condition is also occurred on 30% preliminary vibration. The other results showed that the higher voltage caused the longer distance between main droplets with the satellite.

The different droplet formation process was generated with the actuating waveform with preliminary vibration is shown in Fig. 11. It shows the different kind of droplet shapes; droplet with short connected ligament (a), satellite that joins with the main droplet and became clear droplet (b), droplet with long split ligament (c), and main droplet with satellite (d). We can see the clear droplets without ligament or satellite is at 14V for 50% preliminary vibration waveform. This figure shows that the droplet shape in the high base voltage in the different actuating waveform generated the droplet with long ligament, droplet and severed ligament or more than one drop.

The higher applied voltage in Dowanol ink can evoke the "water gun" effect and generate a long ligament droplet. The larger voltage applied to the actuation waveform, the longer ligament will be generated. The larger voltage means the higher amplitude so then make the head droplet has such a higher velocity and make the tails droplet cannot reach the head droplet. If the short tail combined, then the droplet will become 2 drops, the big droplet is head droplet, with a small droplet from tail droplet so called "satellite".

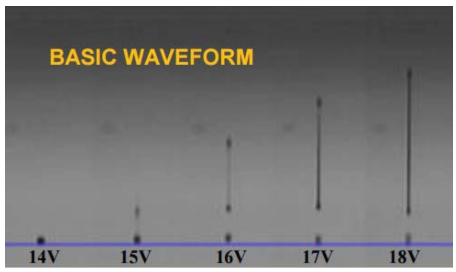


Fig. 9 Droplet shape for basic waveform at 1000 μm from nozzle

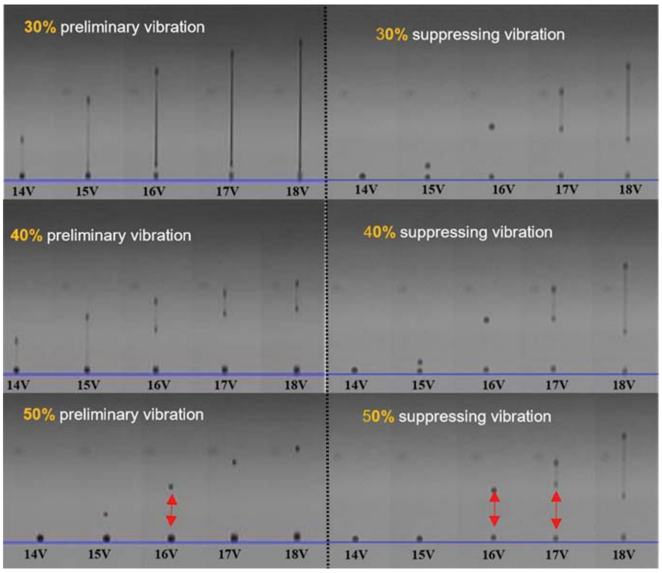


Fig. 10 Droplet shape for preliminary and suppressing vibration waveform

V. The Effect of Voltage and Head Temperature with Different Actuation Waveform to Droplet Volume and Velocity

In previous section, it was described that the droplet shape was influenced by the applied voltage of actuation waveform. The further effect of applied voltage was also presents particularly for the droplet velocity and volume. The different actuating waveform was discussed subsequently.

A. Preliminary Vibration

As stated before, the function of preliminary vibration in actuating waveform is for generate the initial vibration before actual vibration to eject the droplet. Hence, the expected result will be the higher speed and larger volume. The experiment result is shown in Fig. 12 for the droplet velocity and Fig. 13 for the droplet volume of actuating waveform with 30%, 40% and 50% preliminary vibration.

Fig. 12 shows that the droplet velocity for actuating waveform with preliminary vibration 30% at 14-16V applied voltage were higher than the basic waveform, similar velocity at 17 V and lower at 18V. 40% preliminary vibration at 14-15 V generated the higher velocity than basic waveform and then significantly decreased from 16-18V. For 50% preliminary vibration, the generated droplets are with the lower velocity than basic waveform at all base voltage.

This phenomenon can be explained by the observation of pre-experiment to determine the percentage of base voltage as preliminary vibration. In the lower percentage (30%) for base voltage at 14V and 15 V, there is no droplet ejected from the nozzle. It cannot eject the ink from the nozzle orifice because of low energy. The second pulse with high energy supported by pre-vibration without ejected ink caused the higher energy to "push" and ejects the ink, generates the higher initial velocity and higher volume. On the other hand, 50% preliminary vibration will make the droplet come out from nozzle. When it "forth" and "back" or sloshing into the nozzle because of "pull" energy from the second or main pulse, the ink from pre-vibration is combined with the ink from main pulse and subsequently "push" to eject from the nozzle. With the same voltage, the energy to push the greater mass of droplet is similar, make the lower initial velocity of droplet.

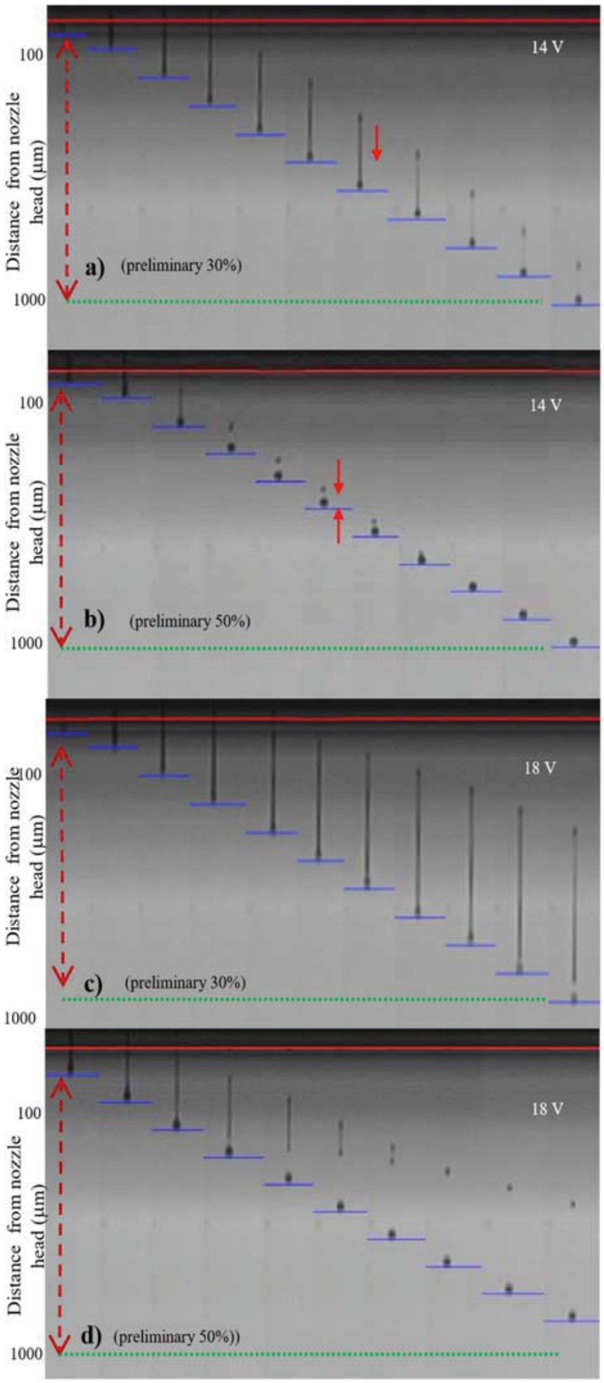


Fig. 11 Droplet formation process for preliminary vibration

The comparison of droplet volume with different percentage of preliminary vibration is shown in Fig. 13. From this figure, we can see that the higher voltage will generate the larger droplet volume. In addition, the percentage of preliminary vibration is in linearity with the droplet volume.

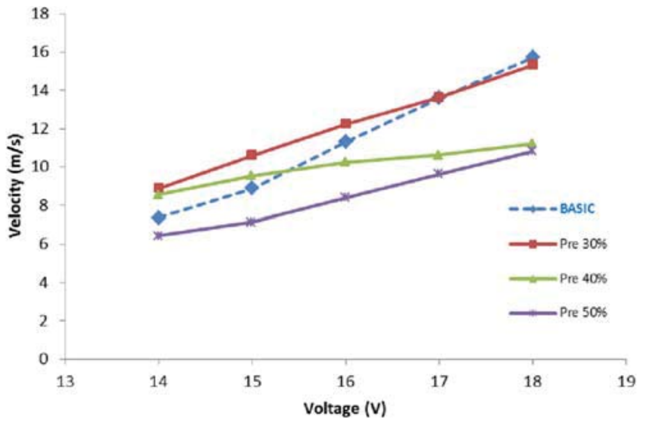


Fig. 12 Comparison of droplet velocity between basic waveform and preliminary vibration waveform

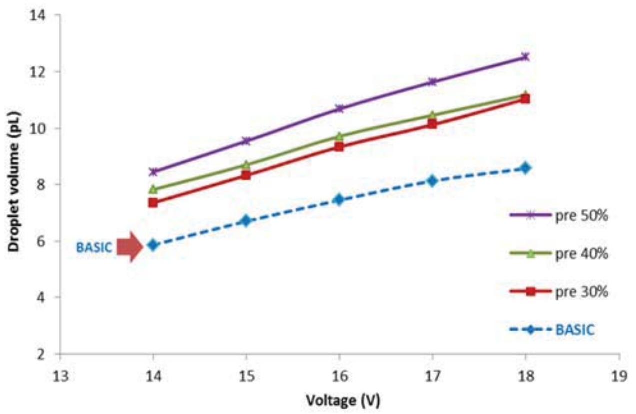


Fig. 13 Comparison of droplet volume between basic waveform and preliminary vibration waveform

The effect of applied voltage related to the actuating waveform in droplet ejection. In this study, we used the negative waveform or pull-push mode in driving the PZT print-head of inkjet printer. The applied voltage on piezo-element enlarges the channel with nozzles, first will generate the positive pressure to increase the droplet volume inside the liquid chamber. The pressure then becomes negative-pressure to push the ink from the nozzle. The higher voltage applied, it would make the higher pressure give to the channel, and it makes the velocity of droplet increase and more fluid can be ejected from nozzle and generated the larger droplet volume.

The other explanation about different phenomenon in droplet velocity for preliminary vibration waveform is by wave superposition principle, similar with measured meniscus motion concept in other study to design waveform [6]. The illustration of wave mechanism is shown in Fig. 14.

The preliminary vibration waveform consists of two waves with same amplitude and wavelength travel in the same direction. First wave is the preliminary vibration with small voltage so that there is no droplet ejection, whereas the second wave is acted as main pulse that supposed to generate the droplet. The exactly same phase of that two waves caused constructive superposition principle, produce a larger resultant at both positive and negative polar include in the residual vibration. The larger percentage of base voltage in preliminary vibration, cause the larger wave resultant in peak ① and generate larger droplet. The larger negative wave in peak ② will generate the larger back pressure such as restoring energy to "withstand" the droplet velocity and caused the lower velocity. The droplet velocity was tending to similar in base voltage percentage (40% and 50%) of preliminary vibration, and higher applied voltage (>15 V).

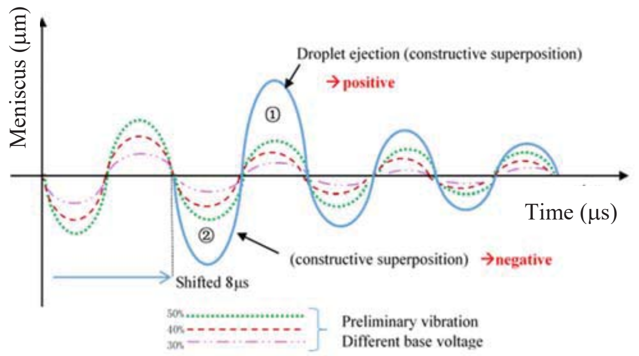


Fig. 14 The description of wave superposition concept in "preliminary vibration" waveform

The head temperature effect to droplet volume is shown in Figs. 15. We also can see the head temperature effect to droplet velocity in different applied voltage from Fig. 16. It present that the higher head temperature will lead the increasing the droplet volume and velocity. This phenomenon can be explained with the Andrade formula. The temperature of ink (T) is influenced the viscosity (η) of the liquid. The Andrade formula for the viscosity (η) is shown in (3).

$$\eta = A \exp\left(\frac{B}{T+C}\right) \tag{3}$$

Some studies about relationships between temperature and viscosity using Andrade equation and the calculation of the viscosity as a function of temperature is described [11], [12]. From that equation, it is determined that the higher temperature, make the lower viscosity. Viscosity of liquid is depends on temperature. Molecular cohesion in a liquid dominates the viscosity. In the higher temperature, the molecules in liquid become more energetic and separated. Therefore, when the cohesive force decreases, the viscosity will decrease too. Malcolm et al. in their study about inkjet fluid characterization stated that in DoD cases, the actuating waveform that generates droplet are affected by ink viscosity [13]. It is determined that for higher temperature of ink, means lower viscosity, will increase the droplet velocity.

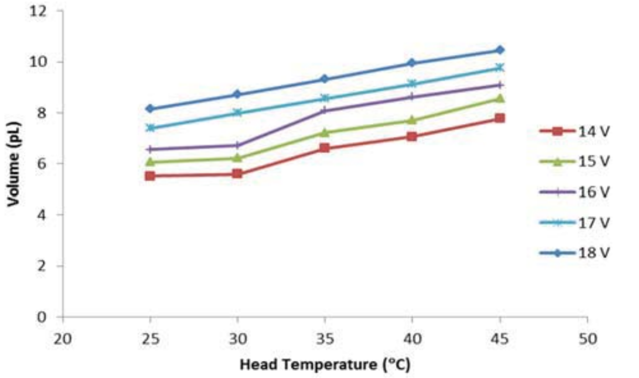


Fig. 15 Droplet volume as a function of head temperature (Basic waveform)

B. Suppressing Vibration

The function of suppressing vibration is to reduce the residual vibration and for suppressing the droplet volume and velocity by shifting the second pulse.

"Suppress A" Waveform: The description of mechanism for Suppress A model is shown in Figs. 17 and 18.

Figs. 17 and 18 present the effect of different voltage of suppressing vibration. Appropriate small voltage could reduce the residual vibration of the main pulse and generated the single peak only from the wave superposition principle. The high voltage could generate new peaks such as multi-pulse that produce multi-drop. Pre-experiment result for determine the percentage of second pulse in the actuating vibration "Suppress A" is shown in Fig. 19.

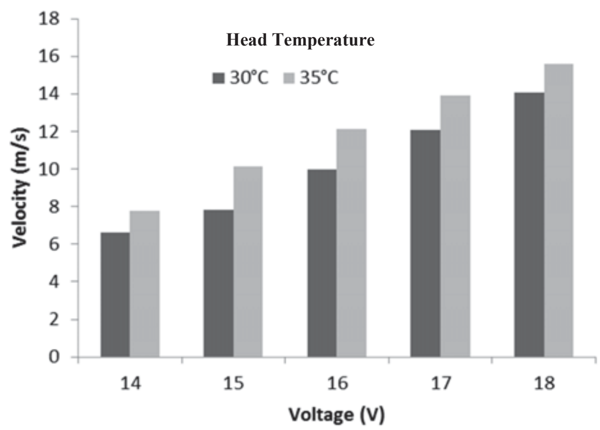


Fig. 16 Droplet velocity as a function of voltage in different head temperature (Basic waveform)

Fig. 19 presents that the percentage of second pulse is only effective to reduce the residual vibration at 30% suppressing vibration particularly in low voltage. There is a significant difference of volume for 100% suppressing at base voltage 17 and 18 V. From monitor display of experiment device, we can see the weeping occurrence. It may be caused by crosstalk effect. Crosstalk in inkjet system is the phenomenon when the actuating waveform from one or more nozzles could unintentionally impact the other nozzles to eject the droplet. High voltage in second pulse could cause undesired pressure perturbations at the other nozzles [2].

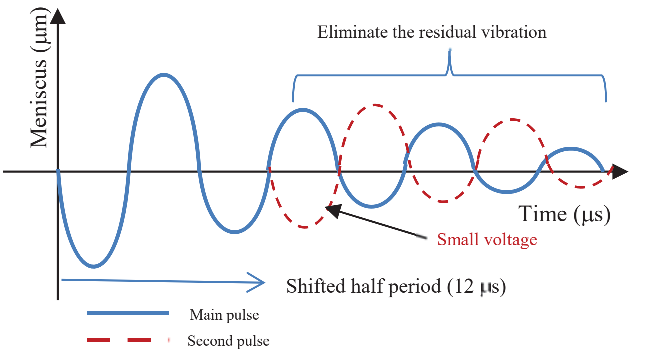


Fig. 17 Description for "Suppress A" waveform output (small voltage)

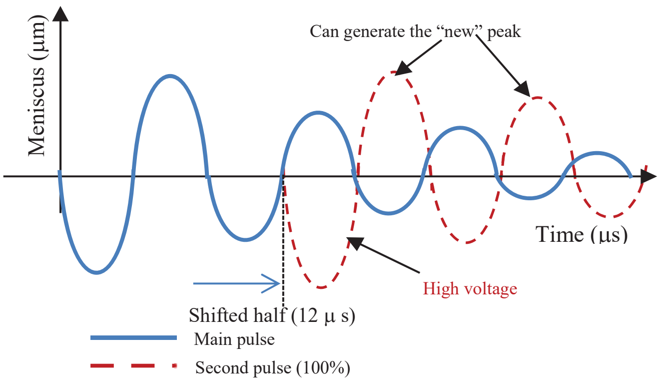


Fig. 18 Description "Suppress A" waveform output (high voltage)

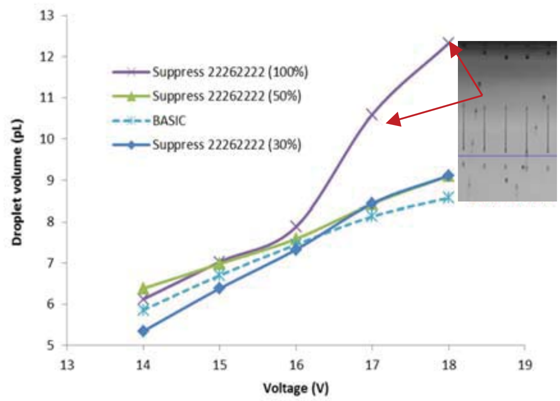


Fig. 19 Pre-experiment result for "Suppress A" (different percentage of second pulse)

"Suppress B" Waveform: Different mechanism of suppressing vibration is shown in Fig. 20. This figure shows wave superposition include the main peak. The shifted period of the second pulse was not fit and cause the impact of suppressing vibration is not significant at the lower voltage. The experiment result is shown in Fig. 20.

Fig. 21 gives the information that the suppressing vibration can effectively suppress the droplet velocity. The significant suppressed velocity is delivered by 50% suppressing vibration, with a clear droplet shape in base voltage at 14 V and 15 V as shown in Fig. 10.

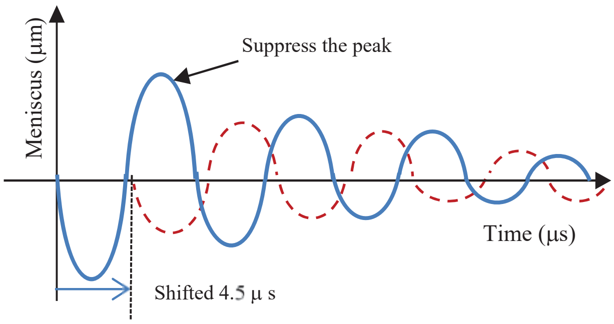


Fig. 20 Description for "suppress B" waveform output

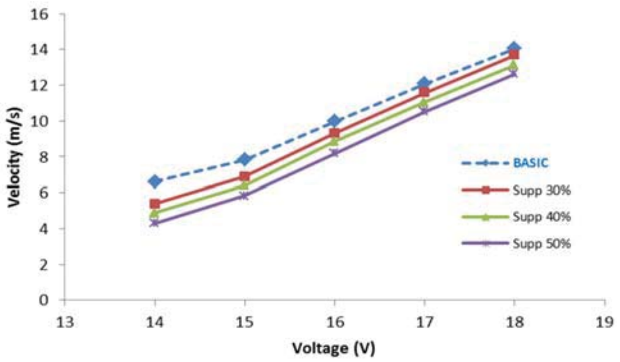


Fig. 21 Comparison of droplet velocity between basic waveform and "Suppress B" waveform

VI. Conclusion

The experimental study was conducted to obtain the actual natural period of experiment device and other parameter as experiment standard. The actual natural period that determined for inkjet printer experiment with Dowanol ink is 8.2643 µs. This result is used to propose 2.066 µs as t_d, t_k, t_u, and t_w input parameter for the actuating basic waveform in the experiment system. The recommendation of fire limitation number standard is 100.000 drops for droplet weight measurement and 1000 µm distance from the nozzle for droplet velocity measurement. This standard is necessary to be implemented for improving accuracies in experiment design and result, an also to increase work efficiency in inkjet printer experiment system.

Preliminary and suppressing vibration can be used to control the droplet size, volume, and velocity. The important point to adjust the droplet velocity and volume is in the voltage percentage of preliminary and suppressing vibration. The 30% preliminary vibration at base voltage 14-16 V and 40% preliminary vibration at base voltage 14-15 V are effective to increase the droplet velocity and volume whereas 50% generated the lower velocity but in a greater volume than basic waveform. On the other hand, 30% of suppressing vibration with input "Suppress A" waveform can be utilized to reduce the residual vibration. 50% of suppressing vibration with "Suppress B" waveform demonstrates its effectiveness to suppress the droplet volume and velocity. With an increase of applied voltage as well as the effect of head temperature, the droplet velocity and volume also increase. The optimum applied voltage is decided by considering the droplet shape which there is no ligament and satellite for each input parameter and it was determined that 14 V is the optimal base voltage.

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