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Statistical Optimization of Process Variables In A Continuous Inkjet Process – A Case Study

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This paper investigates a statistical approach to optimizing the process variables in a Continuous Inkjet Process. In a continuous inkjet (CIJ) process miniaturized fluid droplets are deposited onto substrates for microfabrication. A critical aspect of this fabrication process is the precise generation of droplets based on various input parameters. In this research ultra high speed photography was employed to observe the effect of input parameters such as fluid pressure, frequency, and voltage of a piezoelectric disc on the droplet volume. In order to identify the most significant parameters a factor screening test was performed based on a full factorial design. Based on the ANOVA results, it was revealed that fluid pressure, piezoelectric disc frequency and their interaction were the significant factors that affected the droplet volume. A response surface optimization was conducted to determine the variation on droplet volume based the significant factors. A second-order response surface is established that captures the droplet volume variation over the ranges of the input parameters. The results of this study are vital in determining optimal values of the significant input parameters for microfabrication of electronic devices and micro-electromechanical systems (MEMS) components using direct write technology.

Significance: Precision manufacture of micro-electromechanical systems (MEMS) is primarily based on the selection of appropriate values for critical process parameters. This research presents a second-order response surface model for optimal selection of the significant process parameters for a continuous inkjet process used in MEMS fabrication.

Keywords: ANOVA, continuous inkjet process, design of experiments, MEMS, response surface optimization.

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1. INTRODUCTION

Inkjet based manufacturing techniques enable selective building of miniaturized devices such as micro-electromechanical systems (MEMS) in 3-D space without contact of the tool with the substrate. The modified continuous inkjet (CIJ) technique is one such technique that deposits minuscule volumes of fluid droplets on substrates to build 3-D patterns. Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology (MEMS exchange, 2004). Miniaturized components make the systems faster, more reliable, cheaper and capable of incorporating more complex functions. Fabrication is a critical issue for MEMS based products. The best a MEMS based product can achieve is the performance of its MEMS components (Hadimioglu et al, 2001). Thus if the MEMS part is unreliable, it could render the entire product inoperable. Currently MEMS manufacturing technology is the most underdeveloped segment of the entire MEMS field (Najafi, 2000).Therefore, innovative techniques are needed for the fabrication processes to achieve the goal of making complex and reliable MEMS devices inexpensively. The continuous inkjet technique is a promising technique that offers key advantages over competing microfabrication processes.

In a CIJ system as shown in Figure 1, fluid at high pressure is supplied to the piezoelectric (PZT) modulator assembly. A piezoelectric (PZT) disc within the modulator assembly perturbs the fluid stream. The fluid streams exits the nozzle and is broken into droplets due to acoustic waves generated by the piezoelectric disc perturbation. Droplets of uniform size and spacing are selectively impressed with an electric charge within the charge tunnel (Sweet, 1965). These charged droplets are then deflected using high voltage deflector plates to form features on the substrate. The uncharged droplets are captured by a recirculating gutter back to the tank. This printing process is known as the Continuous Inkjet (CIJ) printing (Sweet, 1971). The CIJ control system consists of a fluid tank which is connected to a pump. A valve manifold is connected with pressure transducer that controls the flow to the print head. The schematics of the CIJ control system and print head are shown in Figure 1 (Heston, 2002). Using the CIJ printing process, a continuous stream of charged droplets can be deflected to desired target regions on the substrate. Extremely high droplet deposition rates ranging between 20kHz to 1MHz make it an ideal candidate for high throughput microfabrication.

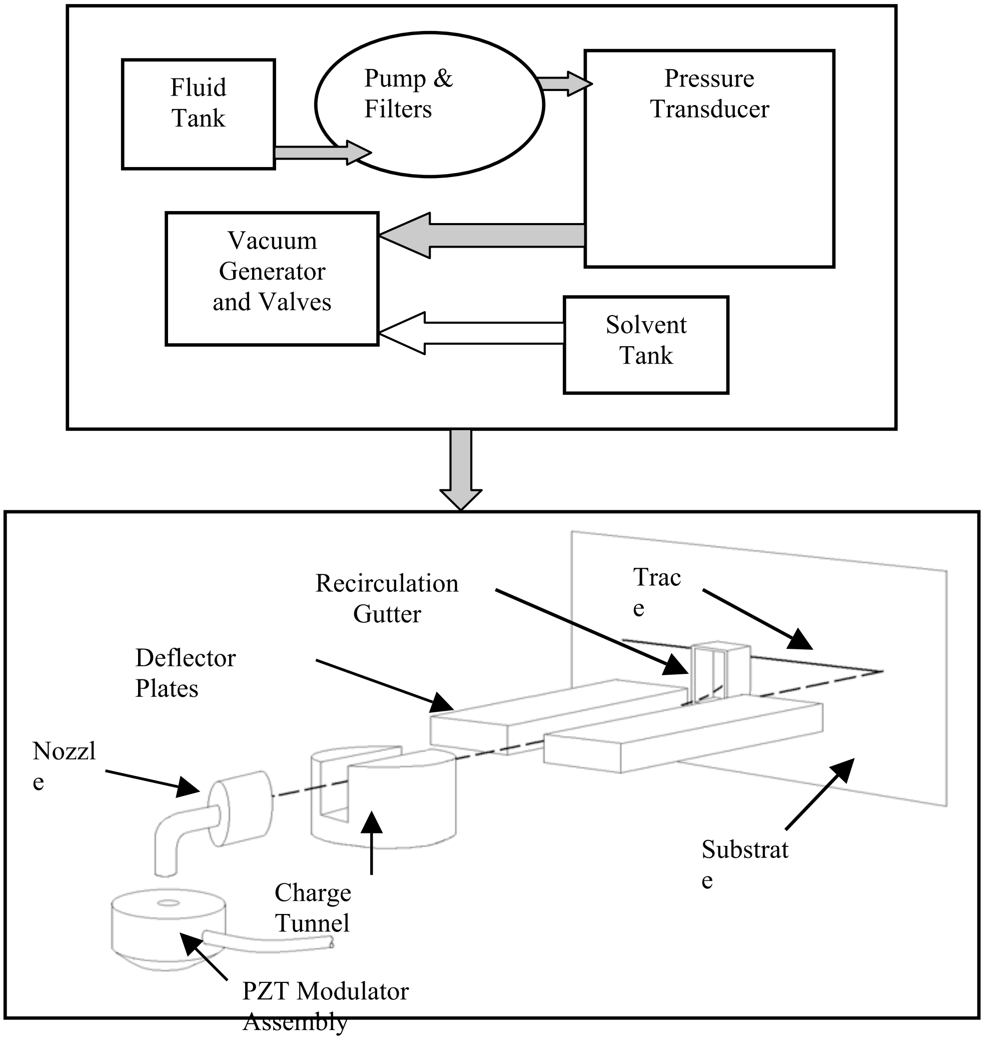

Figure 1. Continuous inkjet (CIJ) control system and print head schematics

2. LITERATURE REVIEW

In earlier studies, researchers have presented analytical (Li S., et al, 2003, Li Q, et al, 2003) and numerical (Ries et al, 1999, Morris et al, 2000, Deitz, 1998) solutions of piezoelectric device deformations. Zhou (2003) at Spectra Inc. has conducted a coupled field analysis of an ink jet print head with shear mode piezo transducer. However this analysis is focused on the drop on demand (DOD) printing concept, which has a relatively simpler drop formation mechanism as compared to the CIJ system. Analytical solutions of piezoelectric device performance generally examine simple shapes (e.g. discs) under static or at resonant conditions. Analytical solutions of complex geometries (as in geometries of actual devices) often involve assumptions, which simplify the stress state and electric field distribution within the device. Invariably, this leads to inaccurate predictions of the observed response. An accurate experimental setup is needed to precisely predict drop formation mechanisms in the CIJ system. Lord Rayleigh (1878) described the theoretical mechanism by which a liquid stream breaks up into droplets. Yeh (2001) has simulated the drop on demand (DOD) inkjet printing process using (Volume of Fluid) VOF concept. Experimental setup to study aero-dynamical motion of CIJ charged droplets revealed that coalescence could easily occur in droplet train proceeding in air and it makes disorder of successive droplet train

(Yatsuzuka, 1997). Keur and Stone (1976) describe the mechanism of drop formation, drop charging, drop deflection, aerodynamic interactions between drops, and limiting factors for a CIJ. Kalaaji et al (2003) perform non-sinusoidal piezoelectric excitation experiments for various values of voltages and phase angle under stable and unstable conditions. In spite of the detailed literature studies of various inkjet systems on both mathematical and experimental fronts, there has been lack in the characterization of the continuous inkjet (CIJ) process with respect to input process variables. Thus it is essential in establishing operating guidelines for optimal printing of miniaturized features using the CIJ direct write process. A Design of Experiment approach was used to obtain the significant factors affecting the response of interest. Further, based on the significant factors a Response Surface Optimization described by Box and Wilson (1951), was conducted to establish trend patterns for the output response (Myers et al., 2002).

3. METHODOLOGY

3.1 Experimental Setup

In order to evaluate the effect of input parameters on the output response (droplet volume) a custom-built continuous inkjet (CIJ) head was fabricated (MacPherson, 2004). Similarly customized hydraulics (Heston, 2002) and electronic circuitry (Maina, 2004) were built to control the input parameters such as fluid pressure, PZT excitation frequency and voltage to the CIJ print head. The commercially available CIJ print head was incapable of generating input parameters at variable ranges, thus there was a need for a custom built head. The experimental droplet generation rate varied from 10 to 80kHz. Thus each droplet is generated every (0.1 milliseconds to 12.5 micro seconds) respectively. In order to capture the dynamics of the flow characteristics of droplet formation, an ultra-high speed camera system (Sensicam, 2004) was used. The image capture resolution at high speeds was dependent on the quality and intensity of the light source. A backlighting technique was used to capture the droplet formation phenomena (Lee, 2003). A 60μm orifice was used within the CIJ print head nozzle. A typical fluid for fabricating electronic traces is nanoparticulate gold colloid in an organic solvent. However due to its limited availability and high cost of using nano gold colloid distilled water was used for the experimentation. Its physical properties are tabulated in Table 1.

Table 1. Physical properties of water

Property	Notation	Value
Density (kg/m^3)	ρ	1e3
Dynamic Viscosity [kg/(m.s)]	μ	1.14e-3
Surface Tension (kg/m^2)	σ	7.28e-3
Contact angle with walls	θ	90°

3.2 Data Collection

Experiments were conducted by varying the pressure, frequency and voltage based on the design matrix. The CIJ process generates micro-droplets at extremely high rates. A typical droplet diameter lies in the range (100 to 180 micrometers) for a 60 micrometer nozzle orifice and is based on the levels of input conditions. The images from the ultra high speed camera system were processed using an image processing and analysis software (ImageJ) (ImageJ, NIH) provided by the National Institute of Health (NIH). The image analysis software allows the establishing of a reference scale so that droplet diameters can be accurately calculated. The image contrast was adjusted to reveal gray scale threshold from the high-resolution pictures (1280X1024 pixels).

4. EXPERIMENTAL DESIGN

4.1 Factor Screening Experiment

One of the critical aspects for achieving optimal print quality for CIJ printing is the precise control of droplet volume. Inconsistencies in droplet volumes can result in inferior fabrication of MEMS devices. Thus it is important to determine the input parameters that affect the droplet volume. Based on literature review and preliminary experimentation it was observed that three factors namely; Fluid Pressure, Frequency and Voltage applied to piezoelectric (PZT) disc affect the droplet volume. However a superficial observance of such trends does not constitute a scientific understanding of the droplet volume. A valid approach to this problem is to run a designed experiment whereby we can statistically conclude our hypothesis. In the current research a 2^3 full factorial design was utilized to study the joint effect of the three factors (k) namely; Pressure, Frequency, and Voltage amplitude on the droplet volume. This is a typical factor screening experiment to determine which of the factors have a significant influence on the droplet volume. The design with eight treatment combinations is displayed as a cube as shown in Figure 2. The low and high levels for each factor are given in parenthesis i.e.; Pressure in psi (10, 20), Frequency in kHz (15, 30) and Voltage amplitude in volts (10, 35). The input factor levels were selected based on operating ranges for a typical CIJ system to be used in microfabrication applications. The response

(Droplet Volume) is measured in picolitres (10^{-15}litres) as the droplet diameters are in (100-180 micrometer) ranges. The details of the 2^k (where k=3) (Montgomery, 1997) design matrix in randomized order is shown in Table 2. As the design is a full factorial design, all the terms are free from aliasing effects and thus we can check for three way interaction effects.

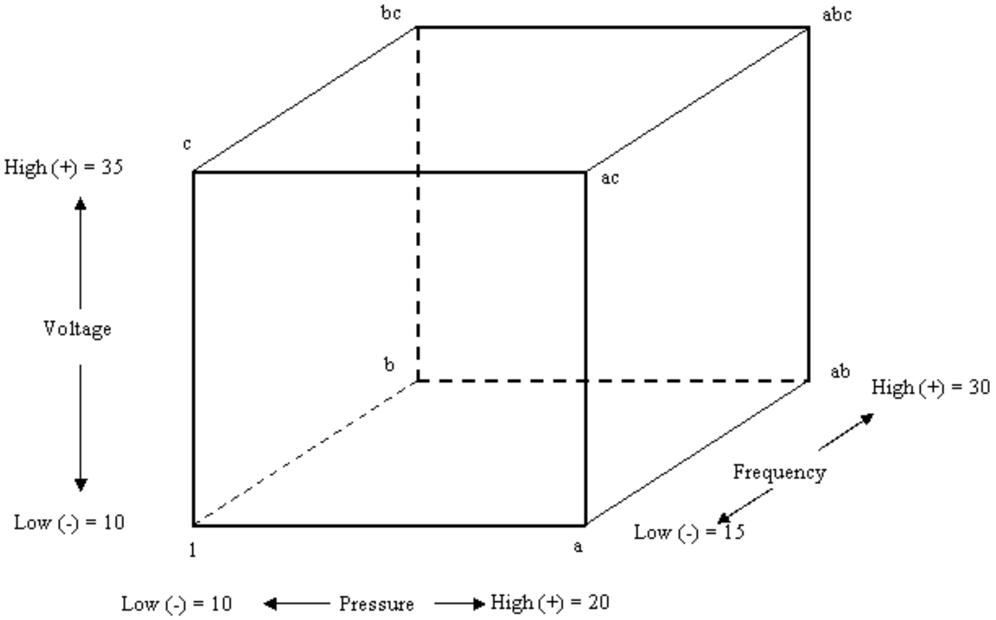

Figure 2. Geometric view of 2^3 factorial design

Table 2. Factorial Design Matrix

No.	Pressure (psi)	Frequency (kHz)	Voltage (V)
1	20	15	10
2	20	15	35
3	20	30	10
4	10	30	10
5	10	15	10
6	20	30	35
7	10	30	10
8	10	30	35
9	20	15	35
10	20	30	35
11	10	15	35
12	10	15	10
13	20	30	10
14	20	15	10
15	10	30	35
16	10	15	35

4.2 Factor Screening Results

An Analysis of Variance (ANOVA) was conducted to determine the significant factors affecting the droplet volume. Table 3 shows the estimated effects and coefficients for Drop Volume in coded units based on an alpha level of 0.05. The R-Sq (adj) value is 99.13% which indicates a well fitted regression model. The R-square statistic represents the proportion of total variation in droplet volume as explained by the regression of droplet volume on the independent variables.

Table 3. Factorial Fit and ANOVA for Drop Volume

Term	**Effect**	**Coef**	**SE Coef**	**T**	**P**
CONSTANT		1671.2	22.13	75.52	0.000
Pressure	983.8	491.9	22.13	***22.23***	***0.000***
Frequency	-1383.3	-691.7	22.13	***-31.26***	***0.000***
Voltage	197.1	98.5	22.13	4.45	0.002
Pressure*Frequency	-581.0	-290.5	22.13	***-13.13***	***0.000***
Pressure*Voltage	88.7	44.3	22.13	2.00	0.080
Frequency*Voltage	-66.3	-33.1	22.13	-1.50	0.173
Pressure*Frequency*Voltage	-293.0	-146.5	22.13	-6.62	0.002

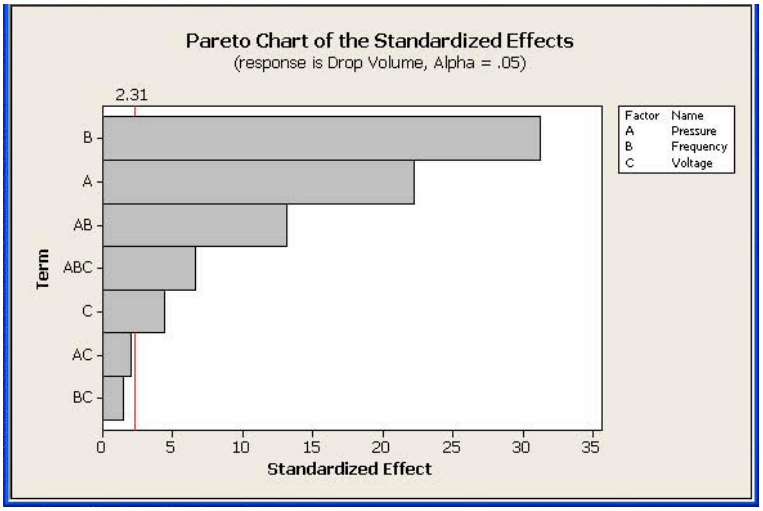

Figure 3. Pareto Chart of the standardized effects

Based on a P value of 0.001 and higher T values the significant factors are Pressure and Frequency. Also the two-way interaction between Pressure and Frequency are observed to play a role in the droplet volume. As shown by the Pareto plot in Figure 3 the significant effects are A: Pressure, B: Frequency, and AB (Pressure-Frequency interaction) that affect droplet volume (response). The findings of the factor screening experiment are consistent with the basic principles of fluid dynamics. From the ANOVA table, frequency has a negative coefficient with respect to droplet volume. This is because, at higher frequencies given that all other factors are held constant, more droplets are created from the same volume of fluid being discharged per unit time. As a result, the volume per drop is reduced based on the frequency of operation. Similarly, fluid pressure has a positive coefficient with respect to droplet volume. This is due to the fact that at higher pressures given that all other factors are held constant, a higher fluid discharge is ejected from the nozzle per unit time. As a result the volume of fluid increases thereby increasing the volume of per droplet. The two way interaction between frequency and pressure are observed to have a negative coefficient. In this scenario the frequency is a dominant factor which cancels the increased volume of fluid due to higher pressure. The next phase of this research involves optimizing the droplet volume based on the two significant factors using a Response Surface Design.

5. RESPONSE SURFACE OPTIMIZATION

5.1 Central Composite Design (CCD)

The factor screening experiment revealed that fluid pressure and piezoelectric disc frequency were the two significant factors affecting droplet volume. In order to investigate this claim further and establish the trend patterns for droplet volume a response surface design was employed. A face centered Central Composite Design (CCD) is utilized for fitting a second-order model to the response surface (Myers, 2002). Table 4 gives the details of the CCD design with two factors.

Table 4. Central Composite Design

Designation	Value
Factors	2
Base Runs	13
Replicates	1
Total Runs	13
Blocks	1
Center axial points	4
Center points	5
Axial points	4
Alpha	1

A geometric view of the central composite design (CCD) is displayed as shown in Figure 69. The lower (-1), axial (0) and higher (+1) levels of each factor are given in parenthesis i.e.; Pressure in psi (20, 30, and 40) and Frequency in kHz (20, 40, and 60). The levels of factors were selected based on wide range of operating conditions of the CIJ print head for microfabrication applications.

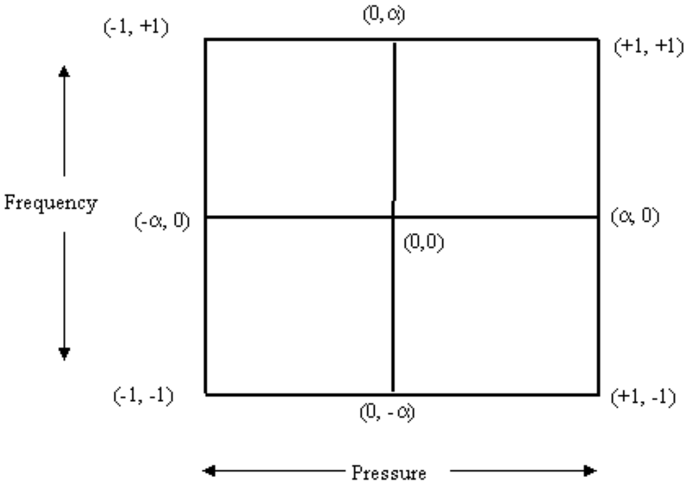

Figure 4. Central Composite Design (CCD) for Droplet Volume in coded units

Table 5 displays the design matrix for CCD at lower, axial and higher levels of the factors in a randomized order. The choice of α = 1 was selected to observe the CIJ system response within the extreme ranges of the operation levels.

Table 5. CCD Design Matrix

No.	Pressure (psi)	Frequency (kHz)
1	40	20
2	30	60
3	40	60
4	30	20
5	30	40
6	40	40
7	20	60
8	30	40
9	30	40
10	20	20

No.	Pressure (psi)	Frequency (kHz)
11	30	40
12	30	40
13	20	40

5.2 Surface and Contour Plot Results for Droplet Volume

An analysis of variance study (ANOVA) was conducted to determine the influence of linear and quadratic regression terms on the droplet volume. Figures 5 and 6 show the Response Surface and Contour plots for the response (Droplet Volume) as a function of the fluid pressure and input frequency respectively. Figure 5 shows that response surface is a second-order model where the droplet volume peaks around 3000 picolitres. It is to be noted that as the frequency increases to 60 kHz the droplet volume decreases and vice versa. This is because at higher frequencies given that all the parameters remain constant there are higher numbers of drops being formed. As a result the resultant droplet volume per drop is reduced in proportion to the frequency of excitation.

It is also observed that at higher pressures the droplet volume increases assuming that frequency and voltage remain constant. This is because at higher pressure more fluid volume is discharged through the nozzle resulting in higher droplet volume per drop. Thus a combination of higher pressure and lower frequency results in a larger droplet volume.

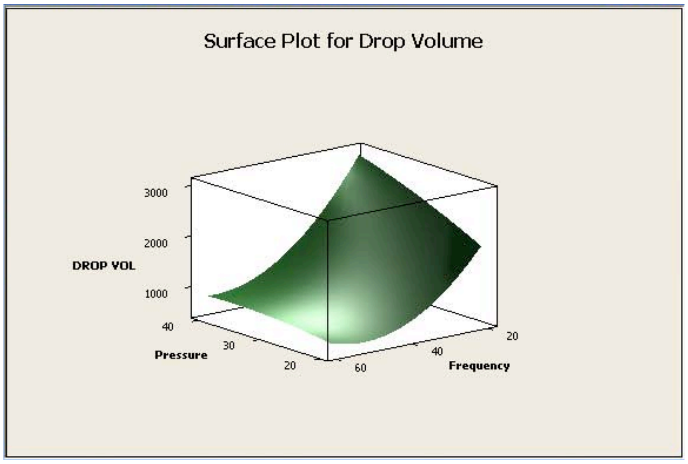

Figure 5. Response Surface Plot for Drop Volume

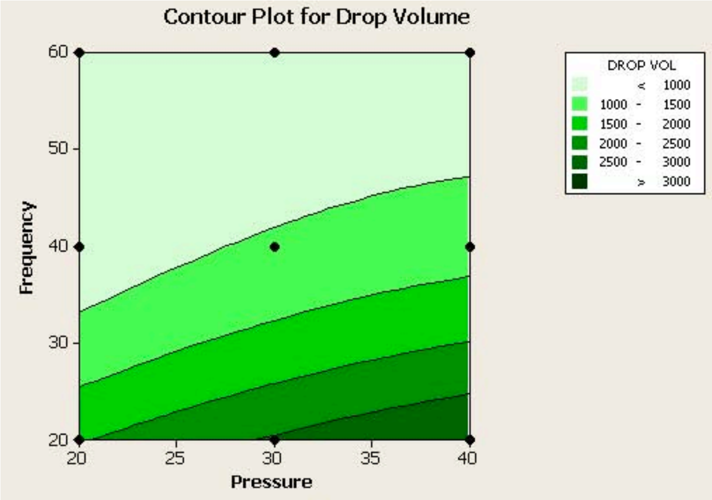

Figure 6. Contour Plot for Drop Volume

The contour plot shown in Figure 6 can be used to interpolate and optimize the droplet volume based on the input parameters. Thus a researcher can select different levels of input settings along the contour line for Pressure and Frequency to obtain an optimal Droplet Volume. The concept of an optimal drop volume is based on the application area. For example, for generating traces on a semiconductor chip the droplet volumes can be to the order of 10 picolitres while the droplet volume for building conductive traces on automobile rear windshields can be to the order of 2000 picolitres and higher depending on the trace width. The regression function for calculating the droplet volume is predominantly driven by the operating frequency of the piezoelectric disc. Equation 1 gives the droplet volume based on inlet Pressure and Frequency.

Drop Volume: DV in picolitres

$$DV = 2396.79 + (114.858*P) - (131.455*F) - (0.677135*P^2) + (1.5103*F^2) - (1.09505*P*F) \quad \ldots \quad (1)$$

Where,
P: Pressure in psi
F: Frequency in kHz

6. CONCLUSIONS

A statistical approach was implemented to study and analyze the influence of process variables in a continuous inkjet process used for micro fabrication. Ultra high speed photography and image analysis methods were utilized to capture spatio-temporal data for the experimental design. Factor screening studies revealed that fluid pressure, frequency of the piezoelectric disc and their two-way interactions are significant factors that affect the droplet volume. A response surface optimization was conducted to establish operating characteristics of the CIJ system with respect to droplet volume. An increase in the fluid pressure resulted in increased (positive coefficient) droplet volume, while increasing the frequency of piezoelectric disc resulted in reduced (negative coefficient) drop volume. From a practical standpoint it is far easier to alter the frequency of piezoelectric disc using standard signal generators rather than employing pumps that can provide wide range of pressure modulations. The maximum droplet volume was found to be 3000 picolitres at lower frequencies and higher fluid pressures. A second-order regression function was fitted that gives a relationship between input parameters and the response (droplet volume). An important insight was gained from this research as related to experimental design method. In traditional process design the alpha (α) level chosen for a design point is usually greater than 1 (approximately $\alpha = 1.41$) However the experimental design relating to the inkjet process optimization had to be face centered (α=1). This is because inkjet related processes work within stipulated operating conditions and extrapolating the operating points is not feasible. In addition, traditional response surface designs specify optimal target value (i.e. either (maxima) high or (minima) low output response value). In our research the optimal response value were based on application domains. Thus the optimal response value would be calculated in between bounds (lower and upper) with a given tolerance value. This work is being further extended to conduct a response surface analysis on other related output responses (e.g. satellite drop formations, etc.). The approach is to superimpose multiple response surfaces to obtain an intersecting region that satisfies all the criteria (similar to multi-criteria optimization). The findings of this research have significant underpinnings for fabrication of accurate, cost-effective and high throughput micro-electromechanical systems (MEMS) using continuous inkjet systems. Researchers and MEMS fabricators can choose appropriate values of input parameters based on their application domain to obtain an optimal drop volume.

7. REFERENCES

1. Box, G.E.P., and Wilson, K.B. (1951). On the experimental attainment of optimum conditions. Journal of the Royal Statistical Society, 13: 1-45.
2. C. J. Morris, F. K. Forster (2000), Optimization of a circular piezoelectric bimorph for a micropump driver, J. Micromech. Microeng., 10 459-465.
3. Deitz, D. (1998), “Connecting the Dots with CFD”, Mechanical Engineering,.
4. Hadimioglu, B., Elrod, S., and Sprague, R. (2001), “Acoustic Ink Printing: An Application of Ultrasonics for Photographic Quality Printing At High Speed,” 2001 IEEE Ultrasonics Symposium, pp. 627-635.
5. Heston, S. F. (2002), “CIJ and Experimental Setup Schematics” University of Pittsburgh.
6. ImageJ software, NIH (2004) http://rsb.info.nih.gov/ij/index.html.
7. Kalaaji, A., Lopez, B., Soucemarianadin, A., and Attane, P. (2003), “Break-up of a Liquid Jet Induced by non-sinusoidal perturbations”, Recent Progress in Ink Jet Technologies II, Chap 4, pp 223-227.
8. Keur, R. I., and Stone, J. J. (1976), “Some Effects of Fluid Jet Dynamics on Ink Jet Printing”, IEEE Transactions on Industry Applications Vol. IA-12, No. 1, pp. 86-90.0
9. Lee, E. (2003), Microdrop generation, (Boca Raton, Fla.: CRC Press).

10. Ries L. L. and Smith S. W. (1999), Finite Element of a Deformable Array Transducer, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 46 (6) 1352-1363.
11. MacPherson Scott (2004), Swanson Center for Product Innovation (SCPI), University of Pittsburgh.
12. Maina Joshua (2004), Department of Electrical Engineering, University of Pittsburgh.
13. MEMS Exchange (2004): Online source http://www.memsnet.org/mems/rd.html.
14. Montgomery, D. C. (1997), Design and analysis of experiments, (New York : John Wiley & Sons)
15. Myers, R. H., and Montgomery, D. C. (2002), Response surface methodology : process and product optimization using designed experiments, (New York : John Wiley & Sons)
16. Najafi, N. (2000), "MEMS Manufacturing Fabrication: Going Back to Basics", Integrated Sensing Systems (ISSYS) Inc., Michigan.
17. Li Q., Lovell M., Mei J., Clark W. (2003), A study of displacement distribution in a piezoelectric heterogeneous bimorph, ASME.
18. Rayleigh, F. R. S. (1878), "On the Instability of Jets", Proceedings of the London Mathematical Society, 10 (4), pp. 4-13.
19. Li S. and Chen S. (2003), Analytical analysis of a circular PZT actuator for valveless micropumps, Sensors and Actuators A 104, pp 151-161.
20. SENSICAM High Speed, CookeCorp Inc., Michigan (2004) http://www.cookecorp.com/bioimaging.html
21. Sweet, R. G. (1965), "High frequency recording with electrostatically deflected ink-jets", Rev. Sci. Instrum, 36, pp.131.
22. Sweet, R. G. (1971), "Signal Apparatus with Fluid Drop Recorder", U.S. Patent 3596275.
23. Zhou Y. (2003), A coupled field analysis of an ink jet printhead with shear mode piezo transducer, Recent Progress in Inkjet Technologies II, Chap 3, Piezoelectrically Driven Ink Jet, pp. 147-150.
24. Yatsuzuka, K., Saito, K, Asano, K. (1997), "Aero-Dynamical Motion of Charged Droplets Ejected from the 26μm Nozzle", IEEE Industry Applications Society Annual Meeting, New Orleans, pp. 1845-1850.
25. Yeh, JT. (2001), "A VOF-FEM and Coupled Inkjet Simulation", Proceedings of ASME Fluids Engineering Division Summer Meeting, New Orleans.

BIOGRAPHICAL SKETCH

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