Sensors and Actuators A 201 (2013) 335–341

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Inkjet jet failures and their detection using piezo self-sensing

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ARTICLE INFO

Article history:
Received 3 March 2013
Received in revised form 28 June 2013
Accepted 24 July 2013
Available online xxx

Keywords:
Piezo inkjet
Inkjet jetting failure
Reliability
Piezo self-sensing

ABSTRACT

As inkjet technology has recently emerged as one of the powerful patterning tools for manufacturing electronic devices, jetting reliability issues have become important. To ensure jetting reliability, jetting monitoring techniques based on piezo self-sensing have been drawn attention to, which detect jet failures due to air bubble entrapment in the printhead. However, the monitoring method based on piezo self-sensing has the capability to detect many other inkjet jet failures. In this study, we investigate the self-sensing signal behaviors in relation to various jet failures other than air bubble entrapment, such as failure of the inkjet head temperature control, abnormal backpressure in the fluidic system, nozzle blockage, etc. To clarify the detectability of various jet failures, we compare self-sensing signals with jet images. From the experimental study, we found that various jet failures can be detected by using the self-sensing signal, and the self-sensing behaviors are different according to the fault causes.

1. Introduction

The application of inkjet technology has broadened from desktop printers, to a manufacturing tool for electronic devices. To ensure productivity and reliability as manufacturing tools, the inkjet jet status needs to be monitored, and jet failures must be identified and fixed immediately. To detect jet failures, the use of piezo self-sensing signals has been proposed [1–5]. A piezo inkjet head uses a piezo actuator to jet ink droplets. On the other hand, the piezo actuator can be used as a sensor, by sensing the force that results from the pressure wave of ink inside the inkjet dispenser. As a practical inkjet monitoring application, the detection of air bubble entrapment in the inkjet head was mainly discussed in most published literature [1–7]. However, few published literatures discuss the self-sensing behaviors in relation to other causes of jet failures. Recently, we have developed an inkjet monitoring system based on piezo self-sensing, to monitor the jetting status of a commercialized multi-nozzle inkjet head [5]. In this study, as an extended work from our previous study, we used the monitoring system to investigate the piezo self-sensing capability of detecting various inkjet failures. The possible causes of jet failures include inkjet head temperature control failure, backpressure control failure, wetting on the nozzle surface, nozzle blockage, etc. To verify the detectability of these jet failures, jet images are acquired for comparison with self-sensing signals. From the experimental results, we found that self-sensing signal behavior was different, according to the causes of jet failures. This can be useful in practice, because schemes for maintenance to correct jet failures can be easily sought, if the causes have been identified.

2. Experiments

Recently, we have developed a low cost and high speed monitoring module, to monitor a multi-nozzle head having 128 nozzles (S-Class, Dimatix, USA) [5]. As an extension of our previous work, we improved the system to use it to monitor a 256 nozzle head (Q-class, Dimatix, USA). Our recent development can be found from the website in Ref. [8]. The detection method is basically the same as our previous work in Ref. [5], and the details will not be discussed further in this study.

Fig. 1 shows a schematic of the experimental setup to investigate the self-sensing behavior in relation to various jet failure causes. Here, to verify the monitoring capability of the self-sensing signal, a drop watcher system based on a strobe light emitting diode (LED) is used to visiualize the jet images.

To determine the jet failures based on the self-sensing signal, reference signals, measured at normal jetting conditions, x_k^r, need to be compared with the monitoring signal, x_k^m. Among other methods for comparing two signals, the cosine value of the signals or variance value has been used in inkjet malfunction detection based on self-sensing signals [4,5].

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http://dx.doi.org/10.1016/j.sna.2013.07.027

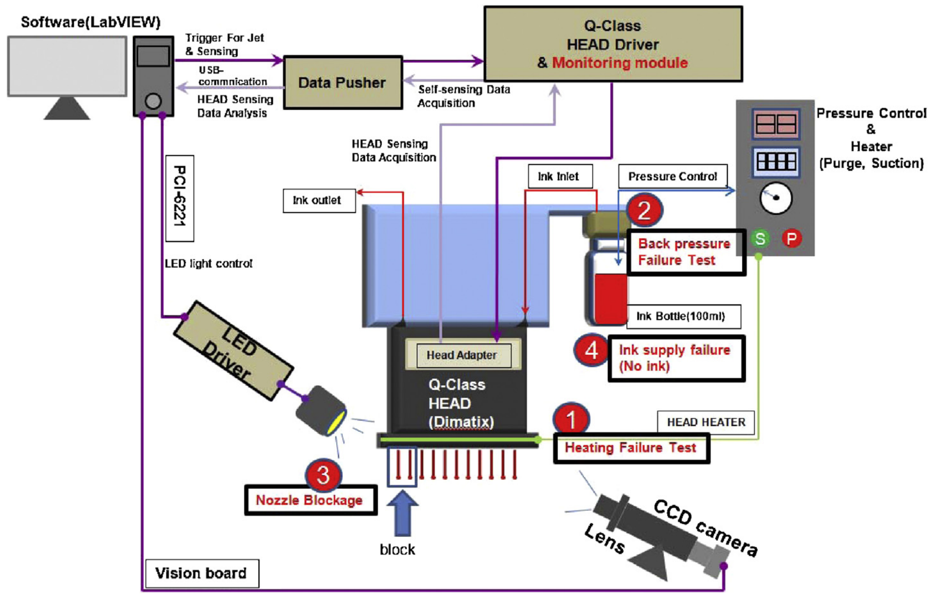

Fig. 1. Schematic of experimental setup.

The value of cosine between the reference and monitoring signals (or vectors), C_k, of nozzle number, k, is defined as [4]

$$C_k = \frac{x_k^r \cdot x_k^m}{|x_k^r||x_k^m|} \tag{1}$$

The cosine value using Eq. (1) mainly detects the phase change of the monitoring signal, with respect to the reference signal. The advantage of using the cosine value is that the value can be normalized, having a maximum value of 1. Here, a cosine value close to 1 means that the jetting status is normal. Robust fault detection can be possible, because it is relatively insentive to measurement noise. However, only critical conditions can be detected, ignoring minor problems, because the value is insensitive to slight signal variation. In some inkjet failure cases, the amplitude of self-sensing signals could mainly be affected with slight, or no phase change. Then, the possible jet failue might not be detected, because the cosine value is close to 1, in spite of signal variation.

On the other hand, the variance value, V_k, has been used for detecting inkjet malfunction based on self-sensing signals [5]. The variance value can be defined as

$$V_k = \sum_{j=1}^{N} \left[x_k^r(j) - x_k^m(j)\right]^2 \tag{2}$$

here, N represent the number of sampled self-sensing data. In this study, V_k is compared to a threshold value, to judge the jetting status [5]. The advange of using Eq. (2) is that slight variation of the self-sensing signal can be effectively detected. Here, the average of self-sensing signals from all jetting nozzles is used as the reference signal, to determine the jetting abnormality of a specific nozzle of interest.

To identify the jet failure causes, more information might be needed, in addition to the variance value using Eq. (2). The possible information includes frequency, phase and amplitude of the self-sensing signal. The software algorithm development required to identify the jet failure causes based on the measured signals is beyond the scope of this work, and needs further study.

2.1. Temperature failure

For jetting fluid, standard inkjet ink (XL-30, Dimatix, USA) was used. For jet consistency, the temperature of head should be controlled, since ink viscosity changes according to the temperature. Fig. 2 shows the viscosity behavior of the ink according to the temperature. Here, the viscosity was measured by use of rheometer (DV-III, Brookfield, USA). The recommended viscosity for the inkjet head (QS-30, Dimatix, USA) is around 8–10 centipoise (cP). To maintain the optimal viscosity for jetting, a heater is placed on the inkjet head, to control the temperature of fluid at 40 °C.

To obtain proper jetting, the proper driving voltage should be used [9]. For this purpose, a simple trapezoidal waveform is used. The rising, falling and dwell time of the waveform were set to 3 μs, and the amplitude of the voltage was set to 75 V, to obtain the jetting speed of 4.7 m/s. Note that the self-sensing signal, as well as the jetting behavior, could be significantly different, according to the driving waveform.

To investigate jet behavior and the self-sensing signal according to the temperature, the setting temperature of the heater on the head was increased from 30 °C to 60 °C. Fig. 3 shows the

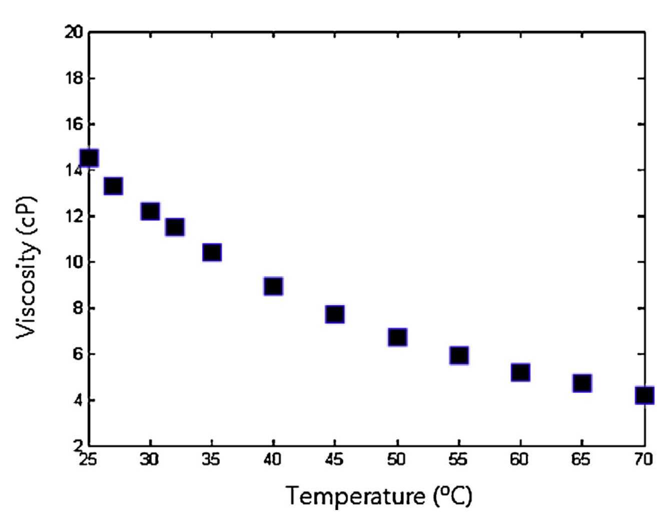

Fig. 2. Viscosity of standard ink according to temperature.

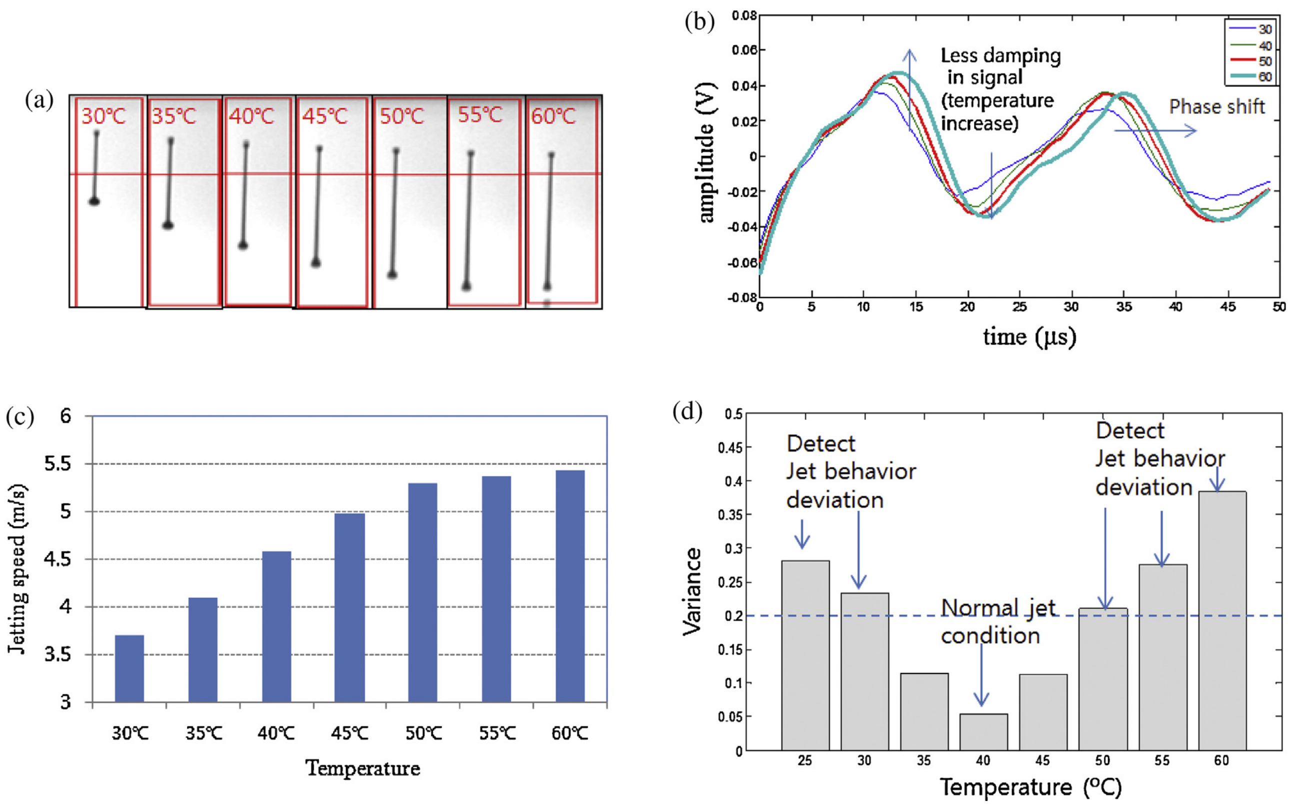

Fig. 3. Temperature effects on jetting behavior. (a) Jet images due to temperature increase. (b) Jetting speed variation due to temperature. (c) Self-sensing behavior according to temperature increase. (d) Variance values according to temperature.

experimental results of the jet behavior, and the self-sensing signals according to the temperature. Here, one of the 256 nozzles (nozzle number: 20) is selected for visual monitoring and self-sensing signal measurement, without loss of generality. As seen in the jet image in Figs. 3(a) and (b), the jet speed increases (or decreases) when the temperature increases (or decreases). Since the trigger delay for the LED light with respect to the jet signal is set to be the same for all of the experiments, droplet images in the downward direction mean higher jetting speed. If the viscosity change of an ink was significant enough to be out of inkjet head operating range, jet failures could occur. However, in this particular ink, we could not observe non-jetting conditions, even when the temperature of the inkjet head is lowered close to room temperature (30 °C), as seen in Fig. 3(a). Note that the jetting speed increase according to the head temperature might be nonlinear, when the temperature reaches 50 °C, as seen in Fig. 3(b). Nevertheless, the temperature effects can be clearly observed from the self-sensing signal, as seen in Fig. 3(c). The self-sensing signals are less likely to be damped out when temperature increases. As a result, the amplitude of the self-sensing signal of higher temperature appears to be slightly larger. Also, slight phase shift (to the right) is observed according to the temperature increase, as seen in Fig. 3(c). The variance value shown in Fig. 3(d) indicates an almost linear increment according to the temperature increase and decrease, with respect to the reference temperature. Note that the jetting speed variation in Fig. 3(b) may not be directly proportionally related to variance value shown in Fig. 3(d). One possible reason is that the self-sensing signal used in this study is related to the residual pressure wave after jetting, rather than the pressure wave accounting for jetting, as discussed in Ref. [5]. The correlation between jetting speed and variance value could be improved if the self-sensing signal during the piezo actuation is included in the variance value. The use of the self-sensing signal measured during the piezo actuation was discussed in Ref. [1].

Note that the signal variation due to slight temperature variation was not significant for this particular ink. As a result, slight jet performance variation due to temperature might not be detected, if the threshold value for the variance is selected at 0.2, as seen in Fig. 3(d). Note that there is non-zero variance value at the reference temperature of 40 °C, because the average of self-sensing signals of all the jetting nozzles is used as the reference signal in Eq. (2). The jet behavior deviations or failures due to temperature control faults are reversible, because the jet condition could easily return to normal, by returning to normal temperature. Also, slight variation of the jetting speed due to temperature is not likely to develop into jet failure. Insensitive variance value change, in the case of slight temperature variation, could be useful in practice, because unnecessary false alarm could be avoided, when used in a monitoring system. Nevertheless, as seen in Fig. 3(d), a deviated jet performance (jet speed) of more than 10% from the nominal jet speed could be detected based on the variance value of the self-sensing signal.

2.2. Backpressure control failure

2.2.1. Decrease in negative backpressure

To avoid wetting on the nozzle surface and ink dripping from the nozzle, slight negative backpressure should be applied to the ink reservoir. However, if the negative pressure increases excessively, air from the nozzles can easily be entrapped in the inkjet head. Furthermore, ink in the inkjet head might flow back to the ink reservoir. On the other hand, if the negative backpressure is not sufficient, there will be jet failures due to wetting on the nozzle surface. Therefore, there is an optimal backpressure to ensure proper jetting.

In this section, the reference backpressure was set to −1.8 kPa. Then, the negative backpressure was decreased, to investigate negative pressure effects. Fig. 4(a) shows the jet images when the

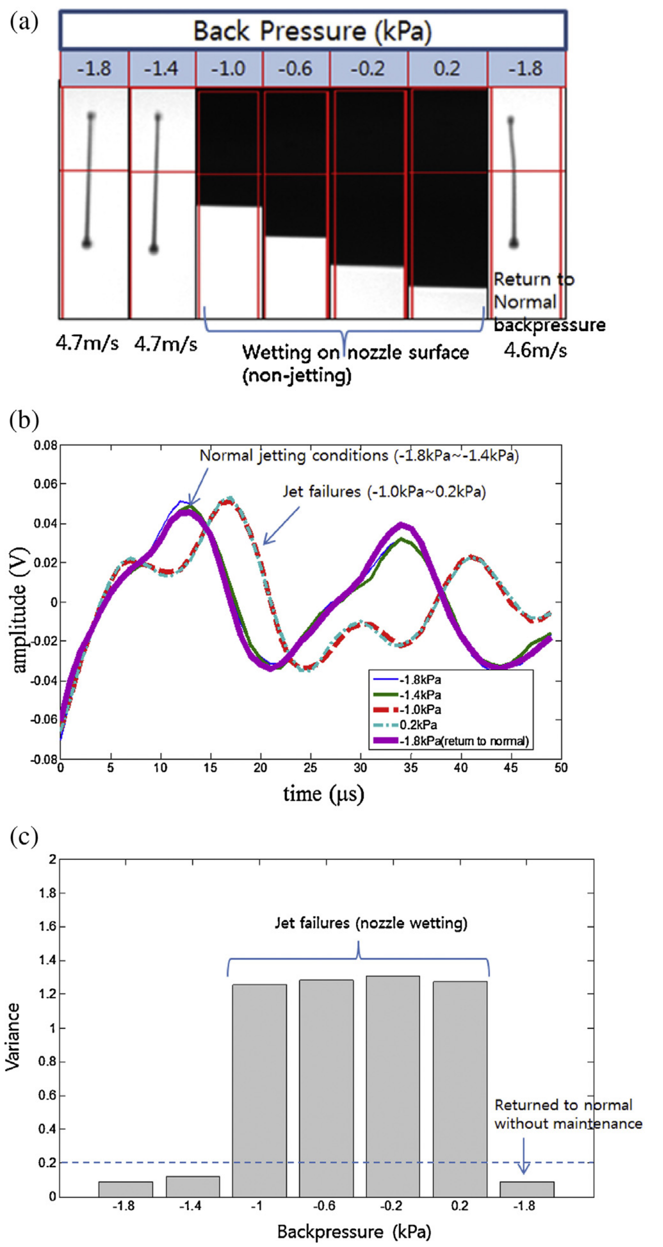

Fig. 4. Decrease in negative backpressure. (a) Jet images in relation to negative backpressure decrease. (b) Self-sensing signal behaviors with respect to negative backpressure decrease. (c) Jet failure detection using variance value.

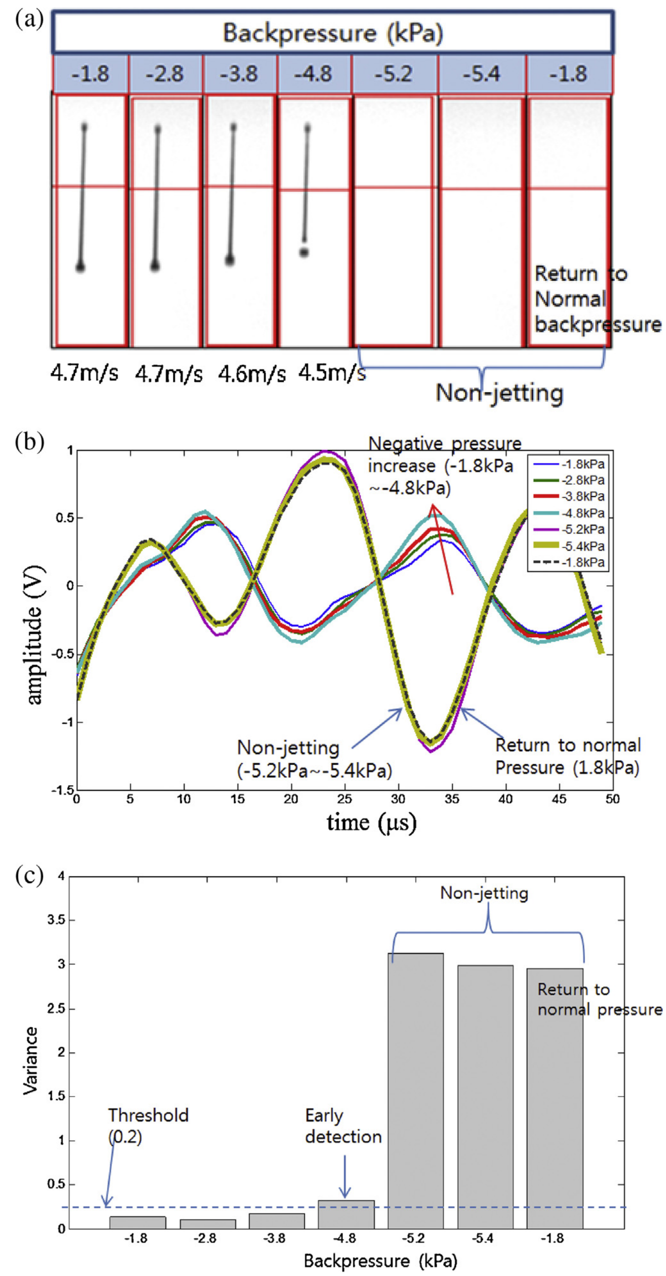

Fig. 5. Increase in negative backpressure. (a) Jet images in relation to negative backpressure increase. (b) Self-sensing signal behavior. (c) Jet failure detection using variance.

negative backpressure decreases from −1.8 kPa to 0.2 kPa. From the experimental results, we found that the jet behavior remained almost the same, as long as the backpressure does not reach the lower limit pressure of −1.0 kPa, as seen in Fig. 4(a). Note that the absolute value for the limit pressure value might differ according to the fluidic system, ink or inkjet head. If the negative backpressure becomes less than the threshold pressure of −1.0 kPa, the nozzle surface becomes wet, and no jet is observed in the acquired images.

Similarly to the jet behavior, the self-sensing signals remain almost the same, in the case of slight backpressure variation. However, if the decrease in negative backpressure is significant enough to result in nozzle wetting, there is significant change in the self-sensing signals. Multiple frequencies are observed in the self-sensing signal, in the case of nozzle wetting, as seen in Fig. 4(b). Here, the main frequency of the self-sensing signal was reduced from 45 kHz to 39 kHz. In previous study, the boundary condition of the nozzle is assumed to be the blocked condition for ink pressure wave propagation [1,10]. Since the nozzle wetting is jetting failure due to the condition of the outside of the nozzle, the self-sensing signal might not be affected by wetting on the nozzle surface, if the nozzle is assumed to be in the blocked boundary condition. However, the experimental results show that jet failures due to nozzle wetting were effectively detected, and the nozzle part is not completely blocked as boundary conditions for pressure wave propagation.

The wetting condition became worse when the backpressure decreased from −1.0 kPa to 0.2 kPa. However, the self-sensing signals remained almost similar, irrespective of the wetting degree, once the self-sensing signal was changed due to the wetting.

Since the self-sensing signal changes significantly in the case of wetting, jet failures due to negative backpressure decrease can be easily detected from the variance value, as seen in Fig. 5(c). The jet failure due to decreased negative backpressure is reversible, since there has been no air bubble entrapment. In theory, the failure can be easily fixed by returning the backpressure to normal, without maintenance process. However, if wiping process of the nozzle surface is not used after returning to normal backpressure, the jet performance, including jet straightness and jet speed, might be affected, due to ink residue on the nozzle surface.

2.2.2. Increase in negative backpressure

In this section, jet behaviors and self-sensing signals are investigated, when negative pressure increases from −1.8 kPa to −5.4 kPa. Then, the backpressure returns to the reference pressure of −1.8 kPa.

As seen in the jetting images in Fig. 5(a), increase in the negative backpressure has negligible effects on jetting, unless negative backpressure becomes close to an upper limit backpressure of −5.2 kPa. When the backpressure becomes close to the upper limit, for example, −4.8 kPa, the abnormal backpressure can be detected prior to jet failures, due to the slight increase in variance value, as in Fig. 5(c). This can be useful, because possible jet failures can be detected at an early stage. When the negative pressure exceeds the limit pressure of −5.2 kPa, air is sucked into nozzles, and entrapped in the inkjet head. In the case of jet failures due to excessive negative pressure, the sensing signals are significantly affected, as seen in Fig. 5(b). Note that the frequency of the self-sensing signal is slightly increased. The possible reason is that the frequency of the pressure wave inside the ink, f, is related to the length of the ink channel, l, and the speed of sound in ink, C as [10]:

$$f = \frac{C}{4l} \tag{3}$$

If air is inserted from the nozzle, the equivalent ink channel length might shorten. As a result, the frequency might slightly increase, based on Eq. (3). In our experiment, the main frequency increased from 45 kHz to 47 kHz, with phase shift close to 180 degrees, as seen in Fig. 5(b). Note that the phase shift effect has significant effects on the variance value.

Jet failures due to excessive negative backpressure are irreversible. Therefore, even if the backpressure returns to normal, the jet condition could not return to normal, unless proper maintenance is performed, as seen in Figs. 5(a–c).

2.3. Ink supply failure

Ink needs to be supplied continuously to the inkjet head during the printing process. If the ink supply system fails to continuously supply ink to the inkjet head, ink filled in the inkjet head will be depleted during jetting, and the jetting will eventually stop. To investigate the effect on the self-sensing signal, ink supply to inkjet head was disconnected during jetting, such that ink in the inkjet channel could be depleted by continuous jetting.

Fig. 6(a) shows jet images acquired when the ink is depleted by disconnecting the ink supply to the inkjet head. Even though the ink supply is stopped, there is remaining ink in the inkjet head channel for a while. As a result, jetting was observed for some period before jetting was stopped, as seen in Fig. 6(a). The imminent jet failures due to ink supply failures can be predicted by the self-sensing behavior in Fig. 6(b), even when the jetting appears to be normal. This is useful information in practice, since the possible jet failures can be detected at early stages, before jet failures occur. The typical self-sensing signal behavior of ink supply failure is significant reduction in the amplitude. As an extreme case where ink is removed from the inkjet head, the signal disappears, since it is related to the pressure wave of the ink inside the inkjet head.

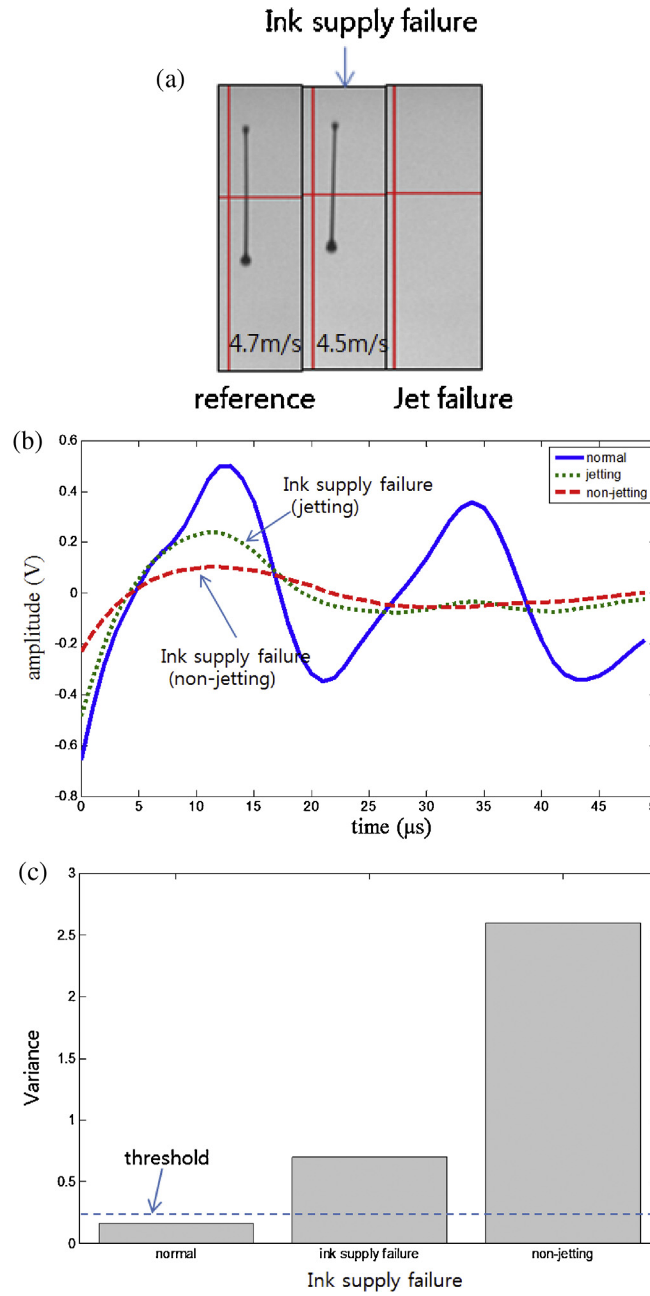

Fig. 6. Ink supply failure. (a) Jet images due to ink supply failure. (b) Self-sensing behavior due to ink supply failure. (c) Jet failure detection via variance.

2.4. Nozzle blockage

One of the most common jet failures may be due to nozzle blockage. There can be two different cases for nozzle blockage: (1) nozzle blockage from debris or dust in the ink; and (2) ink solidification on the nozzle surface. The boundary condition of the nozzle has been considered as a closed condition to explain jet phenomena [10]. Therefore, in theory, the nozzle blockage does not affect pressure waves of ink inside the head, and it is believed that the self-sensing signal (or pressure wave propagation) might not be able to detect jet failure due to nozzle blockage [1,10]. However, the nozzle part may not be a totally closed condition as discussed in previous section, and the pressure wave behavior inside the inkjet head is likely to be affected by the nozzle blockage. To obtain the nozzle blockage condition, several nozzles of interests were blocked by finger

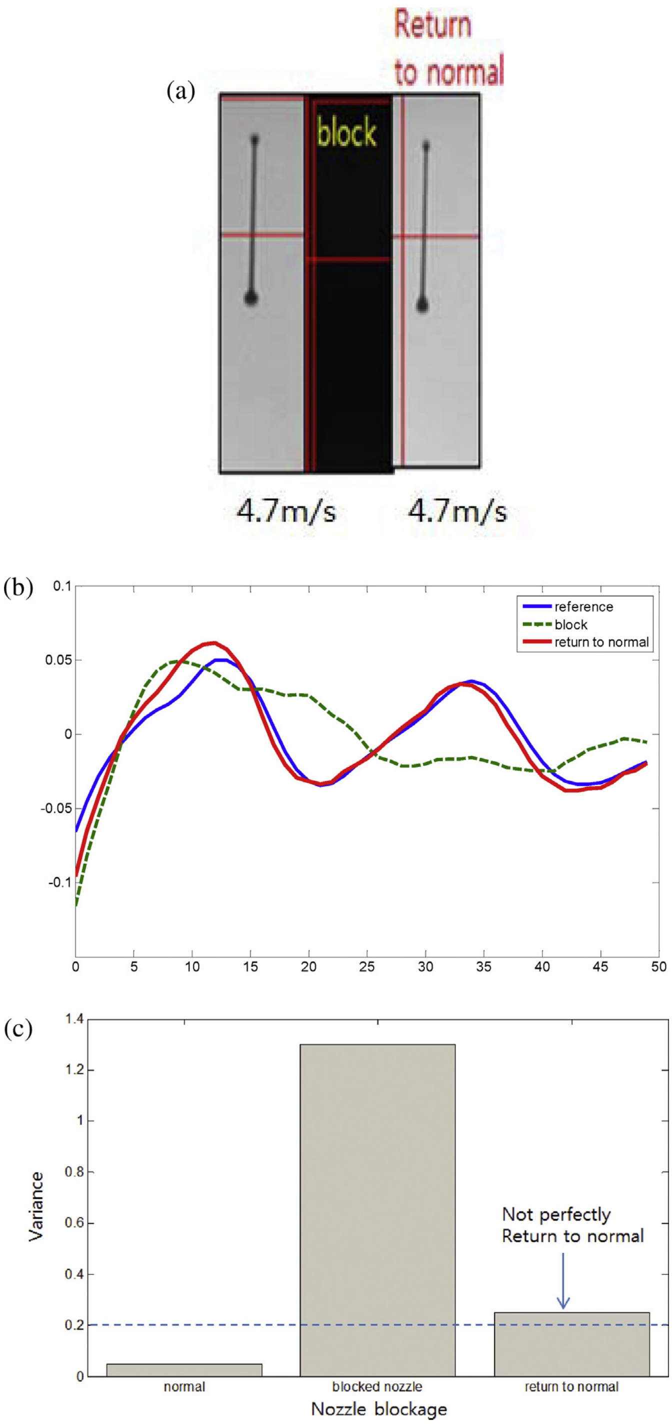

Fig. 7. Nozzle blockage effects. (a) Jet behavior due to blocking nozzle. (b) Self-sensing signals due to nozzle blockage. (c) Nozzle blockage detection by using variance.

pressing of the nozzle surface. As seen in Fig. 7 (b), the nozzle blockage affected the self-sensing signal significantly. The jet failure due to nozzle blockage is reversible, and the jet status easily returns to normal by removal of the nozzle blockage, as seen in Fig. 7(a). Note that it was very difficult to create nozzle blockage conditions artificially. Imperfect blockage from outside during the jet conditions turned some of the nozzles into irreversible jet failure. As a result, when the blockage was removed, some of the nozzles did not return to normal jetting status. One of the possible reasons is air bubble entrapment, due to unstable blocking of the nozzle during jetting. Also, there can be ink residue on the nozzle surface after nozzle blockage removal, and it could affect the jetting condition. As a result, the self-sensing signals behaved differently in our experiments, due to imperfect blockage, and it may need further research to understand self-sensing behavior due to perfect nozzle blockage. Nonetheless, most of the jet failures from artificial nozzle blockage conditions can be detected, by using the self-sensing signal.

3. Conclusions

We investigated the piezo self-sensing behavior in relation to various jet failure causes, including backpressure control failure, ink material property change, nozzle surface wetting, nozzle blockage, etc. From our experimental results, the self-sensing behaviors according to various jet failure causes can be summarized as follows:

1) Temperature
   The low temperature of the head can reduce jetting speed due to viscosity increase or vice versa. In the case of higher viscosity due to low temperature, the self-sensing signal tends to be damped out. The experimental results show that a jet speed variation of 10% could be detected by using the self-sensing signal.
2) Backpressure
   In our experiment, the stable range of backpressure was −1.4 kPa to −4.8 kPa. As long as the variation of the backpressure was within the stable range, the jet behavior and self-sensing signal remained similar to those of the reference backpressure. As a result, slight backpressure variation might not be detected by using the self-sensing signal until it can have potential effects on the jetting behavior. This has advantages in practice since backpressure variation that does not affect actual jet performance can be ignored.
   - Negative backpressure decrease
     Jet failure due to negative pressure decrease is often accompanied by nozzle wetting. This is a reversible jet failure, and it can be easily fixed by returning to normal backpressure. In the case of jet failures due to negative pressure decrease, the self-sensing signal is likely to carry multiple frequencies.
   - Negative backpressure increase
     Jet failure due to excessive negative pressure is related to air bubble entrapment. This is non-reversible jet failure, and it requires significant inkjet head maintenance process, including purging and wiping of the nozzle surface. The variance value tends to be higher than that of negative backpressure decrease, since jet failures that involve air bubbles entrapped in the inkjet head are critical. Typical symptoms of the self-sensing signal show a slightly higher frequency and significant phase shift, compared to the reference signal.
3) Ink supply failure
   In the case of ink depletion due to ink supply failure, the amplitude of the signal can be reduced significantly. In the particular case of an empty inkjet head, the amplitude of the self-sensing signal could be close to zero.
4) Nozzle blockage
   In our experiment, most artificial nozzle blockages were effectively detected via the self-sensing signal. However, a perfect blockage condition was difficult to implement, and it may need further study to understand the self-sensing behavior of a perfectly blocked nozzle.

Acknowledgements

This work was supported by Soonchunhyang University Research Fund and the Mid-career Researcher Program through an NRF grant funded by the MEST (NRF-2013R1A2A2A01004802).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.sna.2013.07.027.

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