A New Method for Recording Tone Images by Electrostatically Extracted Ink Jet

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A new method of recording for tone reproduction was developed by application of the state of ink flight peculiar to the electrostatically extracted ink-jet method. In the state of ink flight in this new method, the ink forms a liquid thread from the nozzle tip, turns into ink corpuscles from the leading edge of the liquid thread, and then scatters like mist. The state of flight from a liquid thread to corpuscles is consecutive and continuous. For expressing tonal differences, the state around the leading edge of the liquid thread was used for recording the high-density area of the image and the state of scattering corpuscles for the low-density area. This differentiation in usage was confirmed workable and favorable results obtained.

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Introduction

The application of ink-jet recording which is low in price and noise has recently been progressing. For this method, water-based ink is mainly used and droplets are used for recording.[1–3] At the same time, studies on the liquid thread formed by using dielectric ink have been reported.[4–9] On the basis of these studies, pragmatic achievements have been made in recording letters and characters. But, it appears that satisfactory results have not yet been obtained for high-quality recording of tone images (for tone reproduction). Along with progress in soft copy technique, the need for a recording technique in the hard copy sphere which is low in price and noise yet high in tone expression will be greater in the future.

For ink-jet recording of tone images, both the dot density control method, where the number of recording dots of a given diameter are regulated per unit of area, and the dot diameter control method, where the diameter of recording dots is regulated in accordance with the tone of the image, are in use. Hertz has reported on his attempt at tone recording where the number of strikes by droplets of a given diameter on the same area are controlled.[1] Improving the quality of images has been difficult because expressing tone with dots by controlling dot diameter and density is correspondingly difficult. To cope with this problem, the tone approximation method in digital recording, utilizing such image processing techniques as the area tone method and the error compensation method, is in major use for tone expression in ink-jet recording. For precise recording of images, however, these methods seem to have limitations. As a way to meet this matter, an analog method of directly recording the information of the image itself without digital processing was considered. The authors have already made application of the state of ink flight peculiar to electrostatically extracted ink jet using dielectric ink to recording for tone reproduction.[10] In the ink flight in this method, ink forms a liquid thread from the nozzle tip, changes into corpuscles from the leading edge of the liquid thread, and then scatters. At this stage of ink flight, the changes from the high-density area of ink corpuscles to the low-density area are continuous. Consequently, an attempt was made to make analog expression of the tone of an image by positive application of this stage of flight. The method which makes differentiated use of the state around the leading edge of the liquid thread for the high-density area of the image and the state of scattering ink corpuscles for the low-density area in accordance with the difference in the tone, was considered workable.

Because ink droplets are conventionally used for recording, reports on the behavior of individual droplets have already been made by observation of the flight of ink jet. For this observation, high-speed cameras and stroboscope were used and periodicity was necessary for ink flight.[2,11,12] In the method that the present authors are investigating, the ink-jet flight has the mixed states of a continuous liquid thread from the nozzle tip and of three-dimensional scattering of the ink in corpuscle form, and the flight of the corpuscles does not have periodicity. It is difficult to make observation of the flight state of such peculiar ink by conventional observation methods. Photography with laser illumination was therefore used for observation of such a state of ink flight.[10]

Observation of the state of ink flight peculiar to electrostatically extracted ink jet using dielectric ink was made and an application of this state of flight to recording for tone reproduction was made. The results obtained were favorable and are reported here.

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Generation of Ink-Jet and the Apparatus for Image Recording

Figure 1 shows the nozzle head section for ink-jet generation. The nozzle is fixed directly onto the inkpot well, 10 mm in diameter and 20 mm in depth. The form of the nozzle is 680 μm in outer diameter, 380 μm in inner diameter, and 15 mm in length. The nozzle tip is cut at a 30° angle to increase the ink response to applied voltage. This angle minimizes deformation of the meniscus (half-moon-shaped convex) formed at the nozzle tip and makes ink response excellent. For formation of the ink meniscus, ink pressure in accordance with the height of the ink surface is used. The electrodes are two metal poles (0.8 mm in diameter) positioned at right angles with the nozzle. The two electrodes are 4 mm apart, connected to each other and, therefore, equipotential. The outline of such an image recording apparatus is shown in Fig. 2. In the nozzle head section, the nozzle and the electrodes are positioned 2 mm apart and the electrodes and the drum are 1 mm apart. The drum is 70 mm in outer diameter and grounded. Direct bias voltage *Vb* of ink itself is applied to the nozzle and image signal voltage *Vs* to the drum. Consequently, a differential voltage (*Vb-Vs*) is applied between the nozzle and the electrodes. The Coulomb force resulting from the difference in voltages makes the ink fly through the middle between the two electrodes. Recording is done with a sheet of recording paper wound around the drum. Image data are derived from signals from a photosensor fixed onto the drum. The image data for input are stored in a floppy disk for the personal computer from the image scanner as density information of 8 bit/pixel with 256 × 256 pixel (or 512 × 512 pixel). The primary scanning was controlled by the pulse motor for the drum and the secondary scanning by the linear motor for the nozzle head section, respectively.

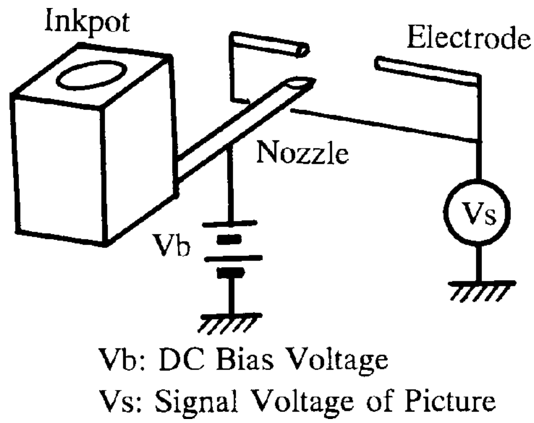


Figure 1. The set up for ink-jet formation.

The Results of Laser Observation of Ink-Jet Flight

For observation of the state of ink flight in the electrostatically extracted ink-jet method using dielectric ink, photography with laser illumination using two kinds of laser beam was used. For observation of the time-average state of ink flying from the nozzle tip to the electrodes, a He-Ne laser beam was used as the light source. With this light source, however, the momentary state of the flying ink cannot be observed. But with a pulse laser as the light source, the instantaneous state of ink flight such as changes in the length and diameter of the liquid thread projecting from the nozzle tip can be observed. Also from the image obtained by photography with pulsed laser illumination, droplet diameters of instantaneous state of fly ink such as changes in the length and diameter of the liquid thread flying from the nozzle tip can be observed.

The Results of Observation by He-Ne Laser Beam. Figure 3 shows the time-average state observed of the ink flight with He-Ne laser beam (shutter speed: 1/30 s) as the light source. As conditions for observation, ink pressure was fixed at 5 mm and voltages 2.5 and 2.8 kV were applied. The results indicated that the state of flight showed the form of the ginkgo leaf with the leaf blade and the stem. The spread of ink was quite narrow in the neighborhood of the nozzle tip, wide past the electrodes, and narrow thereafter. In the ink flight, as the voltage gets higher, the stem portion extends to the right from the nozzle tip and the position where ink spread begins moves to the back of the

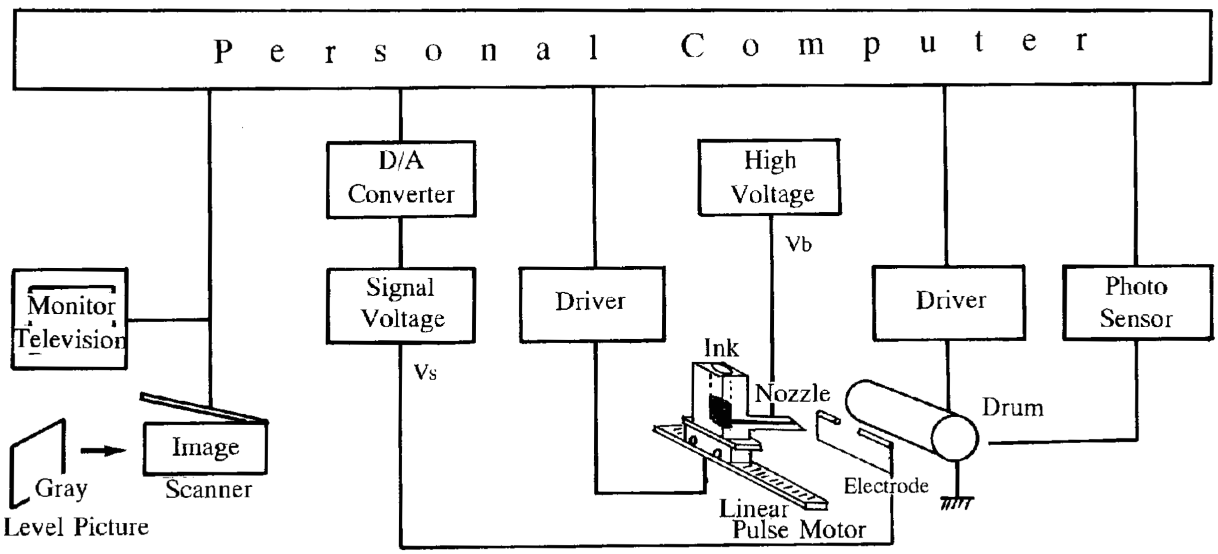


Figure 2. Overall experimental system of tone reproduction by electrostatically extracted ink-jet.

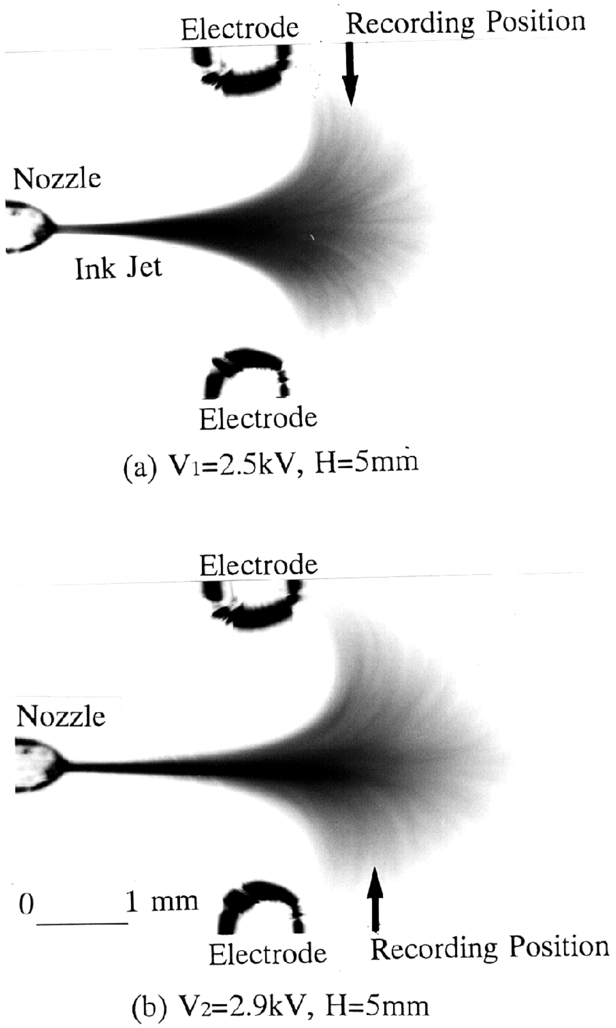
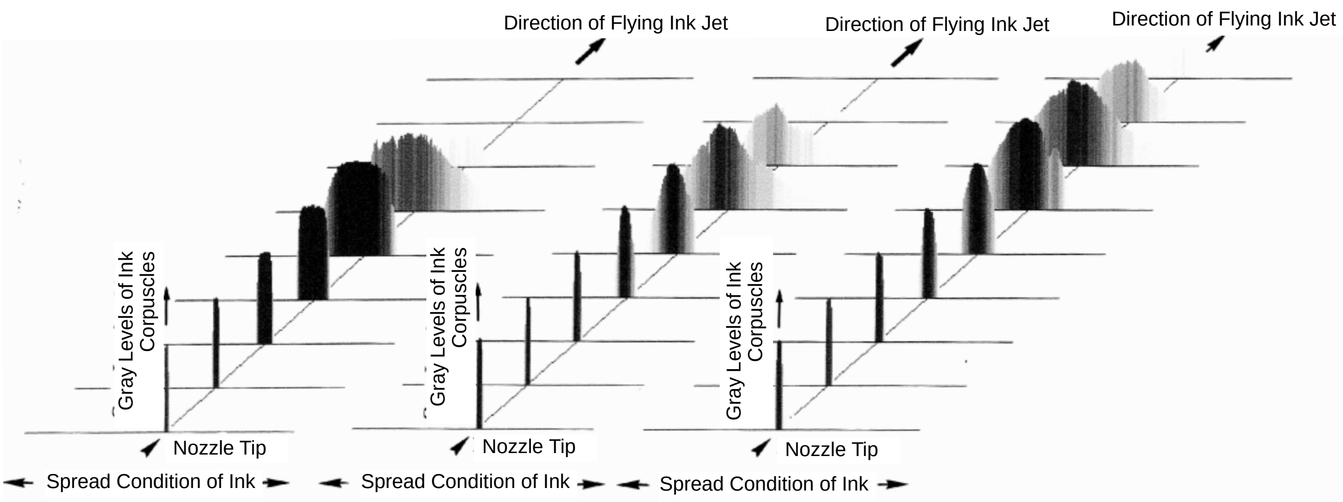


Figure 3. Observation of flying ink-jet by He-Ne laser (Dark field scattering image).

electrodes and the leaf blade narrows. Figure 4 shows the results of three-dimensional presentation of the data of Fig. 3 to determine in detail changes in density of flying ink. This figure shows density distribution perpendicular to the flying ink in16 tones by image processing.

Figures 4(a) and 4(b) show the case with the ink static pressure fixed at 5 mm and the applied voltage 2.5 kV for (a) and 2.9 kV for (b). Figure 4(c) shows the case with ink static pressure at 10 mm and applied voltage at 2.5 kV. These figures show that the density of flying ink is high near the nozzle head and low farther away from it and that the spread of ink is very narrow near the nozzle head, wide farther away from it, and narrow thereafter. With the applied voltage of 2.5 kV and ink pressure changed to 10 mm, in comparison with the 5 mm case, the more extension the stem portion shows in the flight direction of the ink and the lower the density of the ink corpuscles, the smaller the spread of the leaf blade portion.

Figure 5 shows three examples of density distribution of ink observed at the site where the recording paper would be. In the figure, I and II are cases where the ink static pressure was fixed at 5 mm and the voltage changed from 2.5 to 2.9 kV. Rates of changes in the extension and the spread at the site corresponding to the position of the recording paper are about 20% and 48.5%, respectively. The III shows the changes for the case where the voltage was 2.5 kV and ink static pressure was fixed at 10 mm. In this case, the extension and spread at the site for the recording paper are about 26% and 58.2%. These results indicate that the higher the ink static pressure, the higher the density of ink corpuscles may be, and the smaller the ink spread. But the lower the voltage and ink static pressure are, the greater the ink spread is. Figure 6 shows the results of an examination of changes in density of ink corpuscles flying from the nozzle tip through the middle of the electrodes. These results show that with the voltage fixed, the higher the ink static pressure, the lower the density of ink corpuscle, and that with the ink static pressure fixed, the higher the voltage, the smaller the decrease in density. These differences in distribution are considered capable of generating tones in recording.



(a) V_1 = 2.5 kV, H_1 = 5 mm (b) V_2 = 2.9 kV, H_1 = 5 mm (c) V_1 = 2.5 kV, H_2 = 10 mm

Figure 4. Three-dimensional representation of flying ink-jet.

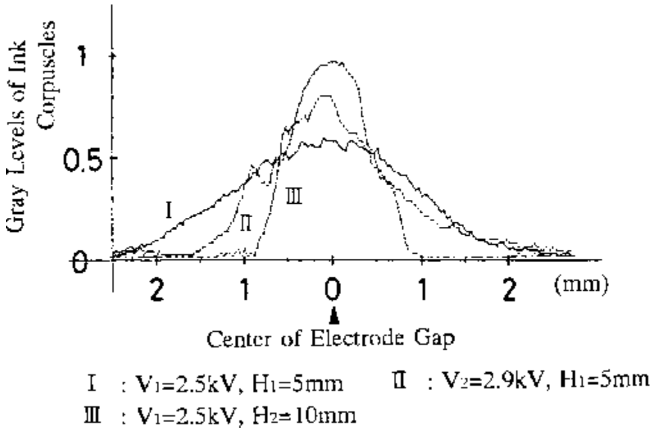


Figure 5. Ink spread dependence on recording position.

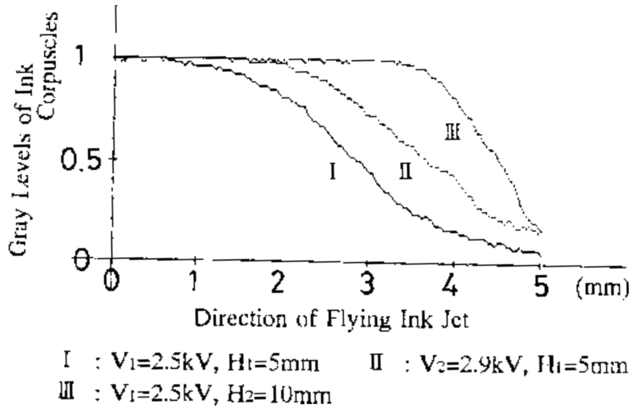


Figure 6. Characteristics of transition state of flying ink-jet.

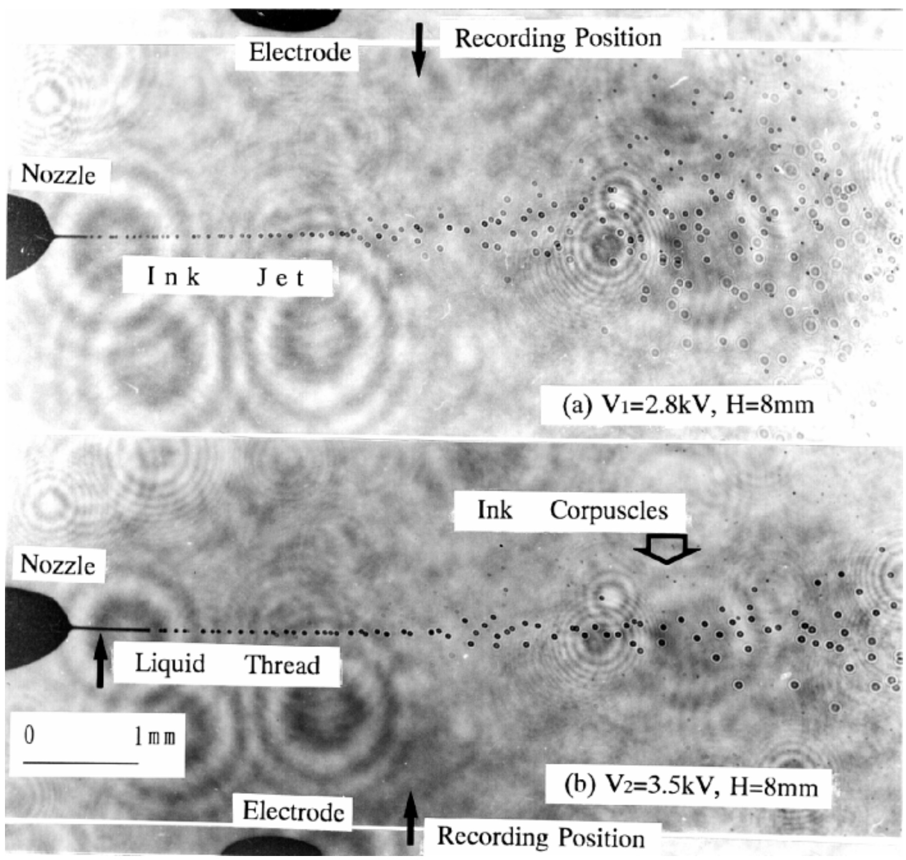


Figure 7. Observation of flying ink-jet by pulse laser.

Results of Observation with Pulse Laser Beam. Figure 7 shows an instantaneous state of ink flight observed with the pulse laser beam as the light source (pulse width 0.4 µs, shutter open). The conditions for observation are ink static pressure fixed at 8 mm and applied voltages of 2.9 and 3.3 kV. This figure shows the stage at which the ink forms the liquid thread, a liquid column is formed from the nozzle head, then changes into corpuscles from the leading edge of the liquid thread, flies past the electrodes, and spreads out. The liquid thread becomes longer as the applied voltage is increased. This figure also shows that the spread of ink becomes narrow at the position for the recording paper. Figure 8 shows dependency of the liquid thread length on voltage, with ink static pressure as the parameter. Liquid thread length was found to be nearly proportional to voltage, i.e., becomes longer with increasing voltage. Figure 9 shows the results of an examination of the dependency on ink static pressure of ink corpuscle diameter and liquid thread length. The corpuscle diameter varies from about 11 to 17 µm in response to the change in ink static pressure from 3 to 15 µm. These changes were found to be approximately proportional to the ink static pressure. For comparison, Hertz obtained a corpuscle diameter of about 18 µm using water-based ink.[1] The corpuscle diameter was not much affected by the applied voltage and was more-or-less constant within the

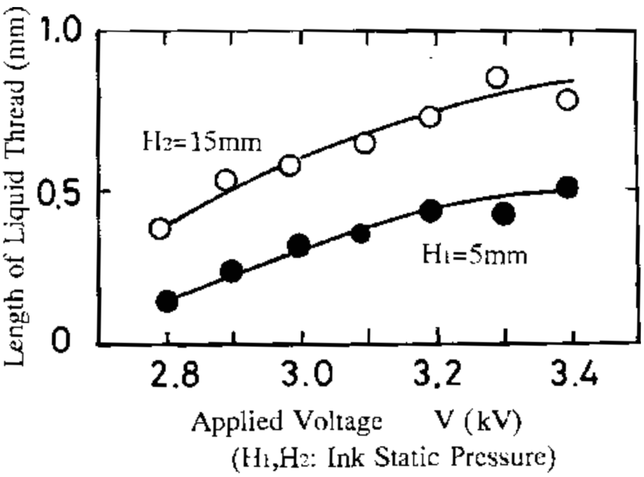


Figure 8. Characteristics of liquid thread length and applied voltage.

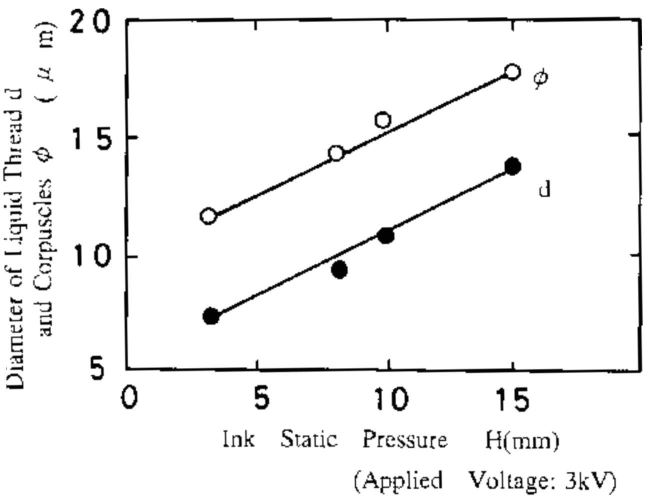


Figure 9. Diameter of liquid thread and diameter of ink corpuscles as characteristics of ink static pressure.

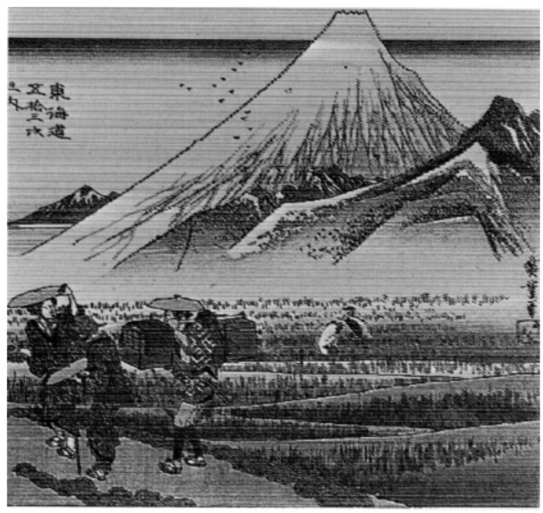
range of voltages used for measurement. Typically, it was about 16 μm when the applied voltage was 3.0 kV and the ink static pressure 10 mm. Therefore, the relationship of changes in liquid thread diameter and corpuscle diameter to changes in ink static pressure is shown here in Fig. 9. Within this range of static ink pressures, the rate of change in diameter is 0.6 μm/mm. The liquid thread diameter was found to be proportional to ink static pressure as well. Changes in liquid thread length are thought to provide the basis for controlling the ink adhering to the recording paper. Consequently, recording of tone images was presumed to be workable by controlling liquid thread length with image signals.

Application to Recording of Tone Images

Three examples of recording of tone images by electrostatically extracted ink jet with use of dielectric ink are shown in Figs. 10(a), 10(b), and 10(c). Figure 10(a) shows the example of recording and reproduction of the image of a woman along with light and shadow tones of the facsimile test chart No. 1 of precise tones (Institute of Image Electronics Engineers of Japan). Figure 10(b) is a trial of recording and reproduction of an ordinary photograph taken as the input image, without much emphasis on tone in comparison with Fig. 10(a). Figure 10(c) shows the recording and reproduction of a woodblock print (Ukiyoe), which has clear outlines and light and shadow tones, used as the input image. On the basis of these recordings, visually favorable results appear to have been obtained.

(a)

(b)



(c)

Figure 10. Recording examples. (a) woman (256 × 256 pixel, 8 bit/pixel); (b) photograph (512 × 512 pixel, 8 bit/pixel); (c) woodblock print (Ukiyoe) (512 × 512 pixel, 8 bit/pixel).

Use of the transition of the ink state from liquid thread to corpuscles depending on the tone, was found workable for recording of images without losing the tones that natural images possess. The changes in position for the ink transforming into corpuscles in relation to liquid thread length is used to control recording density. Controlling liquid thread length was thus found equivalent to changing density for recording. Examinations of recorded images under the microscope show that the transition of the ink state from liquid thread to corpuscles is reflected in the change from high density to low density, respectively.

Conclusion

Observation of the state of ink flight by electrostatically extracted ink-jet with use of dielectric ink and application of ink flight to recording of continuous tone images were described. The state of flight forms the shape of a ginkgo leaf consisting of the stem and leaf blade, regardless of applied voltage and in ink static pressure. Changes in ink spread in the ink flight, liquid thread length, and corpuscle diameter peculiar to this method were clarified as functions of applied voltage and ink static pressure. Accordingly, changes in the state of ink flight have been found to be greater when ink static pressure rather than applied voltage is controlled. It is simpler, however, to control applied voltage rather than ink static pressure. For the present study, therefore, recording of tone images by controlling applied voltage was tried. Thus, an application of the transitional state of ink flight, from liquid thread to corpuscles, to the analog recording of images to reflect tonal differences was found workable. The recording made at the time of atomizing of the ink corpuscles does not give any visually unpleasant effect. Controlling the quantity of ink corpuscles by aperture is not necessary in this method either. The technique is considered especially suitable for recording regions of low density. Further efforts are underway to improve the quality of images.

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