COMPUTER SIMULATION OF OFFSET PRINTING: II. EFFECTS OF VIBRATOR OSCILLATION AND IMAGE LAYOUT

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Keywords: Lithography, Simulation, Inker Dynamics, Ghosting, Starvation

Abstract: This is the second of a series of papers in computer simulation of web offset printing process. The effect of vibrator oscillation on press performance was studied extensively in this paper. The oscillation of vibrators causes a lateral flow of ink across the inking zones of the roller train. The extent of lateral flow of ink increases with the magnitude of vibrator oscillation, and the stroke length is more effective than the oscillation rate. Ink also tends to migrate further away from the input zone as the image coverage of the plate decreases.

A bar graph test form was used to study the dynamic behavior of inkers. Both press time constant and incubation period are independent of any change in ink feedrate, if the ink film thickness is used as the control variable. Dynamic properties vary with the magnitude and direction of ink feedrate change, if the optical density is used as the control variable. The 60-20-20 inker tends to respond to a step change in the ink feedrate slightly faster than the 100-0-0 inker. The oscillation of vibrators does not affect these behaviors, but causes the press time constant to depart from the linear relationship with the reciprocal of image coverage. The larger the stroke length and/or the faster the oscillation rate, the greater the departure. However, the linear relationship of mean ink residence time with the reciprocal of image coverage is not affected by the oscillation of vibrators.

A T-bar test form was specifically designed for appraising print quality attributes such as ghosting and starvation. The oscillation of vibrators significantly reduces starvation, but has a negligible effect on ghost. The larger the stroke length and/or the faster the oscillation rate, the less the starvation. Ghost is slightly more severe if the heavy coverage is placed closer to the leading than the trailing edge. The 100-0-0 inker

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produces slightly less ghost and less starvation than the 60-20-20 inker. These results of computer simulation are presented in this paper. Implications to closed-loop control of the printing process are also discussed.

Introduction

The oscillation of vibrators was neglected in the first of this series of papers in the computer simulation of web offset printing process. It was found in the first paper that the printed ink film thickness, rates of ink flowing through each of the three ink form rollers and to the web, and quantity of ink built up in the inker all followed a first order differential equation for step changes in ink feedrate, from which the press time constant and incubation period were derived (Chou and Bain, 1996). If the ink film thickness is used as the control variable, both press time constant and incubation period are independent of the ink feedrate change, regardless of its direction and magnitude. If the optical density is used as the control variable, the press responds to a step increase in ink feedrate faster than a step decrease and, in some cases, the response to a large change may be faster than a small one. The former observation appeared to contradict, but the latter was consistent with, the results reported in the literature (Neuman and Almendinger, 1977; Chung and Chung, 1992). In fact, both observations are correct and the apparent discrepancy could be attributed to the non-linear relationship between optical density and ink film thickness (Chou and Harbin, 1991).

It was also found in the first paper that the press time constant and mean ink residence time are both inversely proportional to the image coverage. The mean ink residence time is indeed an upper limit estimate of the press time constant (MacPhee, 1986). This finding is very important to the control of printing process. A densitometer is commonly used in the pressrooms for measuring the optical density of color control bars in order to monitor the printing process. If the optical density deviates from the target value, the ink feedrate is adjusted accordingly. Another print sample is often taken long before the press reaches the steady state, and unnecessary ink key adjustment is made. Thus, the pressmen change ink key settings constantly throughout the entire press run. Excessive print waste and inconsistent print quality may result from this practice of chasing after the target density.

The simulation results also show that the 100-0-0 inker produces an ink film slightly more uniform than the 60-20-20 inker does. This is ascribed to the second and third ink form rollers of the 100-0-0 inker whose major function is to smooth out the ink film laid down on the plate by the first form roller. The dynamic response to a step change in ink feedrate is faster for the 60-20-20 inker than the 100-0-0 inker, due to multiple ink delivery paths of the former compared to the single path of the latter and to the less bulky ink volume of the former inker. Each inker configuration apparently has its own advantages. Selection of an inker may depend on personal preference or needs.

The aforementioned findings were obtained in the absence of vibrator oscillation. In reality, all of the vibrators of a lithographic printing press oscillate during printing in order to prevent the formation of ink ridges on the inking rollers. The oscillation action causes a lateral flow of ink across the inking zones and hence changes the ink distribution behavior of an inker. The simulation methods reported by Scheuter and Rech (1970) and MacPhee (1995) did not take into account the oscillation of vibrators. This paper will present the methodology that includes the oscillation of vibrators and focus on its effect on inker performance.

Press dynamics and print quality are the most important criteria for appraising the capability of an inker design. The former characterizes the rate of a press responding to a change of ink or fountain solution feedrate. The faster the press can respond, the faster the process can reach the steady state. That is, the more stable is the process and hence the more consistent print quality and the less print waste it will produce. The latter characterizes the image-related variations of ink film thickness that cannot be compensated by ink key adjustment. These ink film thickness variations, commonly known as ghosting and starvation, will be discussed in detail in this paper.

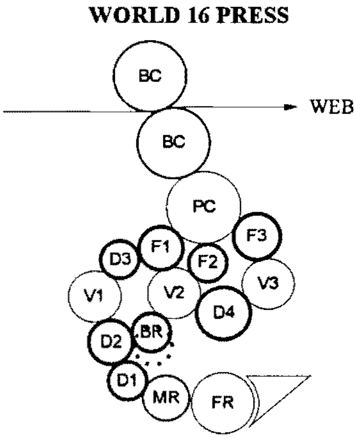

Figure 1. Schematic diagram illustrating the roller configuration of World 16 press used in this computer simulation.

Computer Simulation Methodology

The World 16 press manufactured by Goss Graphic Systems was simulated in this study. The inker can be toggled between 100-0-0 and 60-20-20 roller configurations by pushing a button on the press control panel that throws the bridge roller (BR) off (dotted circle) or on (solid circle), as shown schematically in Figure 1. This allows a direct comparison of press performance between the two roller configurations. The methodology of computer simulation discussed hereinafter can, nevertheless, be applied to any other inkers.

In the computer simulation, the surfaces of all inking rollers and plate and blanket cylinders are divided into many small cells of the same size, as shown schematically in Figure 2. The number of cells between two adjacent roller nips in the printing direction has to be rounded off to the nearest whole number. The number of cells across the roller is also rounded off to the nearest whole number. The cell size selected in this study is 0.25" by 0.25". There are 91 cells around the press cylinder and 140 cells across the press for a 35" web.

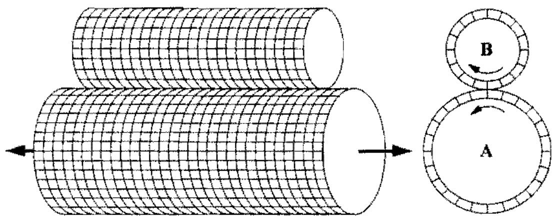

Figure 2. Schematic diagram showing the roller surfaces divided into many small cells. Each cell contains ink film thickness information. Roller A is a vibrator.

To simplify the computer simulation, the following assumptions were made.

1. There is no squeeze flow of ink in any direction in the roller nips.
2. There is no roller slippage and ink piling in the nip entrance.
3. The film splitting is smooth and no ink is lost from the interacting cells.
4. All the rollers rotate simultaneously one cell in the printing direction in each time interval.
5. The effect of fountain solution on ink distribution and ink transfer is ignored.

The first three assumptions are required for the conservation of ink volume involved in ink distribution. That is, the inflow of ink to two interacting cells is the same as the outflow. The assumption of no squeeze flow is needed for neglecting the dot gain and for disallowing the lateral flow of ink across the inking zones other than that caused by the oscillation of vibrators. The distribution of fountain solution in the inker and ink-water interactions complicate tremendously the simulation of printing process. It will not be taken into consideration in this paper.

The ink film thicknesses at the exit of any inking roller nip, e.g. ink distribution from Vibrator A to Roller B illustrated in Figure 2, can be expressed by the following equations:

$$H_B'(i,j) = S_{AB}\left[H_A(k,j) + H_B(i,j)\right] \quad (1)$$

and

$$H_A'(k,l) = (1 - S_{AB}) \left[H_A(k,l) + H_B(i,l) \right] \qquad (2)$$

with,

H_A : thickness of inflow ink film on Roller A,
H_B : thickness of inflow ink film on Roller B,
H_A' : thickness of outflow ink film on Roller A,
H_B' : thickness of outflow ink film on Roller B,
i, k : indices specifying the cell positions around the rollers,
j, l : indices specifying the cell positions across the rollers,
S_{AB} : split ratio specifying the fraction of ink in the roller nip distributed to Roller B.

The relationship between indices j and l is governed by the oscillation of vibrators and can be expressed by the following equation.

$$l = j + L_S \sin(2\pi v N + \phi) / N_C \qquad (3)$$

with,

L_S : stroke length,
v : oscillation rate,
ϕ : phase angle,
N : number of plate cylinder revolutions, i.e., time of printing,
N_C : number of cells per unit length across the rollers.

The second term on the right hand side of Eq. (3), which is rounded off to the nearest whole number, is the number of cells that the vibrator travels laterally. The oscillation rate of vibrators is generally specified in relation to the plate cylinder revolutions in the United States and to the vibrator revolutions in Europe. The American system is used in this paper, for example, the oscillation rate of 1:6 means that the vibrator completes one cycle of oscillation every 6 plate cylinder revolutions. The phase angles of 0, 120, and 240 degrees are adopted in this work for the three vibrators to minimize the net momentum of axial movement. The stroke lengths of 1/2" and 5/4" and the oscillation rates of 1:6 and 1:3 were selected in this work to explore the effect of vibrator oscillation on inker performance.

For nips involving an ink form roller and the plate cylinder, the fractional image coverage of each cell on the plate cylinder has to be included in the distribution equations as follows.

$$H_P'(i,j) = S_{FP}\left[H_P(i,j) + H_F(k,j)\right] \quad (4)$$

and

$$H_F'(k,j) = F(i,j)\,(1 - S_{FP})\left[H_P(i,j) + H_F(k,j)\right] + \left[1 - F(i,j)\right]H_F(k,j) \quad (5)$$

with,

H_P : thickness of inflow ink film on the plate cylinder,
H_F : thickness of inflow ink film on the ink form roller,
H_P' : thickness of outflow ink film on the plate cylinder,
H_F' : thickness of outflow ink film on the ink form roller,
F(i, j) : fractional image coverage of cell P(i, j) on the plate cylinder.
S_{FP} : split ratio specifying the fraction of ink in the nip transferred to the plate.

Using radiotracer techniques, Bradford (1954) found a split ratio of 0.42 in the thick-film region, and the split ratio became proportionately less as the ink film became thinner. Mill (1961) observed experimentally a split ratio of nearly 0.5. Wirz (1964) found a split ratio of 0.4 for the nip between ink form roller and plate cylinder. The effect of split ratio on the ink film thickness distribution was explored by Guerrette (1985). Because the split ratio of 0.5 is commonly used in the calculation of ink distribution on the inking rollers (Hull, 1968; MacPhee, 1995), this value is adopted for all roller nips in this study.

Press Dynamics

The bar graph shown in Figure 3 was used as the test form to study the dynamic behavior of inkers. The left and right pages of the bar graph test form consist of solid and halftone bars, respectively. The image coverages of those bars vary from 10% to 100% in an increment of 10%. The image coverage is indicated by the number underneath each bar. The width of each bar is equal to the width of an ink fountain key, and there are six cells across each bar. The ink feedrate to each inking zone was set in proportion to the image coverage of that zone. The simulation process, starting with a clean inker, included four stages of varying ink feedrate. The target thickness of ink film on the substrate was 1 μm at the first stage, increased to 1.5 μm at the second stage, brought back to 1 μm at the third stage, and the ink feed was completely terminated at the fourth stage. The press was allowed to run for 520 plate cylinder revolutions at each stage.

Ink Film Thickness Profile

Figure 4 shows the ink film thickness profiles of the solid bar with 100% image coverage obtained from the 500 to 520 plate cylinder revolutions of the 100-0-0 inker under three different oscillation conditions. In the absence of vibrator oscillation (Figure 4A), the ink film thickness is practically constant at 1 μm thick with fine fingerprints corresponding to the ghosts of the plate cylinder gap produced by the form rollers (Chou and Bain, 1996). Because the oscillation of vibrators causes a lateral flow of ink across the inking zones, a fluctuation of ink film thickness around the target value of 1 μm is expected. It is not surprising to observe that the ink film thickness profiles also take the form of sinusoid and their periods coincide with the oscillation rates of vibrators, as shown in Figures 4B and 4C.

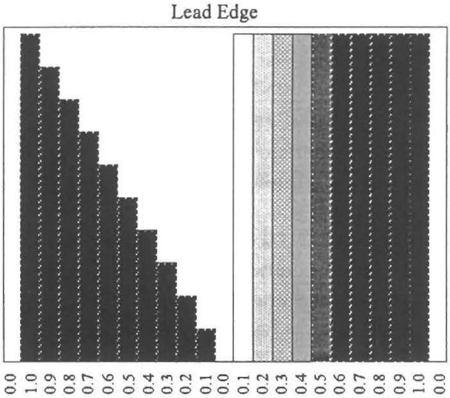

Figure 3. Bar graph used as the test form to study the dynamic behavior of inkers. The number underneath each bar indicates the image coverage of that ink input zone.

The question about whether this periodic variation in the ink film thickness on the press sheets can be detected by human eyes is of great interest. The differences in the maximum and minimum ink film thicknesses are respectively 0.012, 0.065, and 0.044 μm for the three charts shown in Figure 4. It is very difficult to visualize those differences in thickness. So, the ink film thicknesses are converted into optical densities using the equation proposed by Calabro and Savagnone (1983) as follows.

$$\frac{1}{D} = \frac{1}{D_S} + \left(\frac{m}{H}\right)^n \qquad (6)$$

with,

D : optical density,
H : ink film thickness,
D_S : saturation density which is the density of an ink film of infinite thickness or the maximum density that can be achieved by an ink,

m : density smoothness which characterizes how fast the ink mileage curve approaches the saturation density,

n : power law index which is generally implemented to improve the fitness of equation to the experimental data.

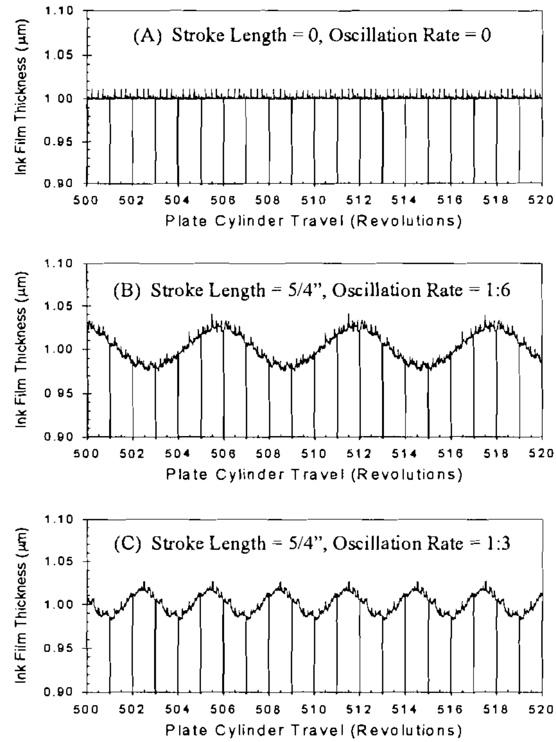

Figure 4. Ink film thickness profile of the 100% solid bar obtained from 500 to 520 plate cylinder revolutions of the 100-0-0 inker under different oscillation conditions.

Searching through our data base, the following set of parameters was accepted: D_S = 1.59, m = 0.5972, n = 0.8965. These parameters convert a 1.0-μm ink film on a substrate, whose optical density is 0.21, to an optical density of 1.0. Then, the corresponding differences in terms of optical density become 0.004, 0.023, and 0.016. The optical density difference in the latter two cases may be detectable only if there is an abrupt change of the image on the same press sheet such as the ghost image to be discussed later. It is unlikely to detect such a gradual transition in the optical density variation over several plate cylinder revolutions. Similar observations were also made for simulation results of various image coverages obtained under different oscillation conditions. It is concluded that the oscillation of vibrators does not bring in any visible impact on the uniformity of ink film on a press sheet.

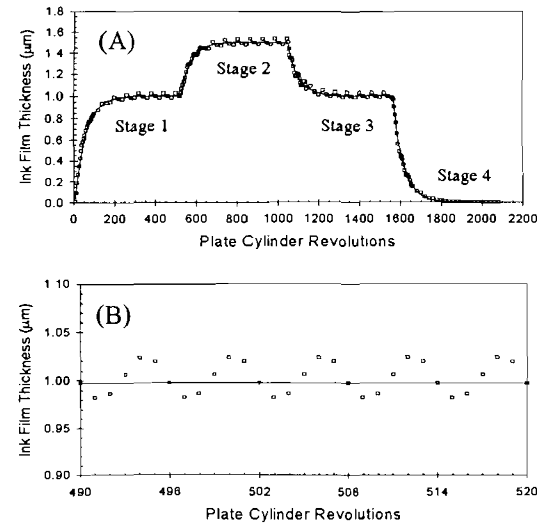

Figure 5. Dynamic behavior of printed ink film of the 100% solid bar obtained from the 100-0-0 inker under the oscillation conditions of SL = 5/4" and OR = 1:6. Chart B is a close-up view of chart A.

Dynamic Behavior

Figure 5 illustrates the average printed ink film thicknesses of the 100% solid bar as a function of plate cylinder revolutions obtained from simulating the 100-0-0 inker under the oscillation conditions of 5/4" stroke length (SL) and 1:6 oscillation rate (OR). The solid lines are drawn through the data points according to the first order differential equation reported by Neuman and Almendinger (1978) as follows.

$$H = H_o + (H_\infty - H_o)\left[1 - \exp[-(N - N_d)/\tau_p]\right] \quad (7)$$

with,

H : thickness of ink film on the substrate,
H_o : initial ink film thicknesses before a step change in ink feedrate,
H_∞ : steady-state ink film thicknesses after a step change in ink feedrate,

N : number of plate cylinder revolutions,

N_d : incubation period or delay time which is the time elapsed before the output begins to respond to the step change.

τ_p : press time constant characterizing how fast the process reaches the steady state, e.g. the inker will achieve 63.2%, 95.0%, and 99.3% of the steady state after 1, 3, and 5 τ_p impressions, respectively.

Table 1. Press time constant of solid bars as a function of image coverage obtained from the analysis of ink film thickness for the four inking stages of the 100-0-0 inker under the oscillation conditions of SL = 5/4" and OR = 1:6.

Image Coverage	Stage of Ink Feed 1	2	3	4	Mean	Standard Deviation
0.1	123.64	123.39	123.89	123.55	123.62	0.182
0.2	103.09	103.17	103.09	103.09	103.11	0.036
0.3	78.35	78.58	78.24	78.40	78.39	0.122
0.4	59.50	59.71	59.42	59.55	59.55	0.107
0.5	47.54	47.65	47.47	47.57	47.56	0.063
0.6	40.15	40.22	40.13	40.17	40.17	0.035
0.7	35.52	35.56	35.51	35.53	35.53	0.019
0.8	33.28	33.31	33.27	33.28	33.29	0.016
0.9	35.52	35.57	35.53	35.53	35.54	0.019
1.0	50.14	50.15	50.17	50.15	50.15	0.010

Table 2. Incubation period of solid bars as a function of image coverage obtained from the analysis of ink film thickness for the four inking stages of the 100-0-0 inker under the oscillation conditions of SL = 5/4" and OR = 1:6.

Image Coverage	Stage of Ink Feed 1	2	3	4	Mean	Standard Deviation
0.1	16.33	16.48	16.27	16.48	16.39	0.093
0.2	8.85	8.83	8.90	8.95	8.88	0.047
0.3	6.16	6.14	6.23	6.25	6.20	0.045
0.4	6.38	6.37	6.45	6.46	6.42	0.041
0.5	6.91	6.95	7.00	7.00	6.97	0.039
0.6	7.12	7.15	7.20	7.21	7.17	0.034
0.7	7.01	7.06	7.09	7.10	7.06	0.033
0.8	6.55	6.61	6.63	6.64	6.61	0.035
0.9	5.37	5.44	5.44	5.45	5.42	0.032
1.0	3.98	4.20	4.12	4.06	4.09	0.083

Close examination of Figure 5B reveals that the period of average ink film thickness variation also coincides with the oscillation rate. This fluctuation in the ink film thickness does not affect the fitness of Eq. (7), however. The press time constants and incubation periods derived from Eq. (7) for the solid bars produced by the 100-0-0 inker are listed in Tables 1 and 2, respectively. Statistical data are also included in the tables. It is noted that both press time constants and incubation periods of all four stages are, from the statistical viewpoint, the same for each image coverage. Similar results were also obtained from the halftone bars as well as those of the 60-20-20 inker under various oscillation conditions. The incubation periods and press time constants obtained from the rates of ink flowing through each of the three form rollers and to the web, and the quantity of ink built up in the inker are also independent of ink feedrate change for both 100-0-0 and 60-20-20 inkers. All of these results indicate that the dynamic response of an inker is independent of the ink feedrate change, regardless of its direction and magnitude. The oscillation of vibrators does not affect this behavior.

Table 3. Incubation period and Press time constant of solid bars as a function of image coverage obtained from the analysis of optical density for the four inking stages of the 100-0-0 inker under the oscillation conditions of SL = 5/4" and OR = 1:6.

Image	Incubation Period				Press Time Constant			
Coverage	0-1μ	1-0μ	1-1.5μ	1.5-1μ	0-1μ	1-0μ	1-1.5μ	1.5-1μ
0.1	6.36	27.90	13.43	19.25	78.91	221.29	109.37	140.09
0.2	2.68	17.30	6.97	10.98	64.22	180.20	90.97	116.81
0.3	2.60	11.49	5.09	7.53	48.45	133.49	69.23	88.59
0.4	3.48	10.36	5.57	7.47	37.66	98.21	52.90	66.86
0.5	4.06	10.75	6.14	7.97	31.05	75.62	42.60	52.97
0.6	4.32	10.98	6.36	8.15	26.86	61.99	36.20	44.46
0.7	4.40	10.64	6.32	7.97	24.01	54.25	32.09	39.25
0.8	4.31	9.61	5.99	7.38	22.29	51.66	29.96	36.90
0.9	3.76	7.55	5.01	6.01	22.80	57.90	31.61	39.86
1.0	2.26	7.60	3.65	4.91	30.98	82.06	44.31	56.53

It was found in the first paper that if the optical density is used as the control variable, the press responds to a step increase in ink feedrate faster than a step decrease (Chou and Bain, 1996). This phenomenon was ascribed to the non-linear relationship between optical density and ink film thickness. Eq. (6) and the ink mileage parameters presented therein were used to convert ink film thickness into optical density. An equation identical to Eq. (7) was used to fit the optical density data, from which the incubation period and press time constant were derived. Table 3 summarizes the incubation period and press time constant obtained from the same data set as that of Tables 1 and 2. The results indicate that the response to a step increase in ink feedrate is faster than a step decrease; the response to a large increase in ink feedrate is faster than a small increase; and the response to a small decrease in ink feedrate is faster than a large decrease. Similar behavior was also observed for the results obtained under various oscillation conditions of both 100-0-0 and 60-20-20 inkers. It is concluded that if the optical density is used as the control variable, the dynamic response of press is controlled by the magnitude and direction of ink feedrate change, regardless of the oscillation conditions.

It was also found in the first paper that the press time constant is proportional to the reciprocal of image coverage in the absence of vibrator oscillation (Chou and Bain, 1996). Figure 6 shows that this linear relationship becomes worse, the more vigorous the oscillation of vibrators. The slope also decreases with increasing magnitude of oscillation. It is obvious that the oscillation of vibrators causes the ink to flow laterally from high to low coverage zones and hence the net ink throughput rate increases in the low coverage zones and decreases in the high coverage zones. Accordingly, the press time constant is increased in the high coverage zones and decreased in the low coverage zones. Referring to the test image in Figure 3 of which the image coverage decreases progressively from both edges toward the center, a reversed trend in the thickness of printed ink film on the substrate was observed (Figure 7). This chart further supports the hypothesis of lateral flow of ink from high to low coverage zones.

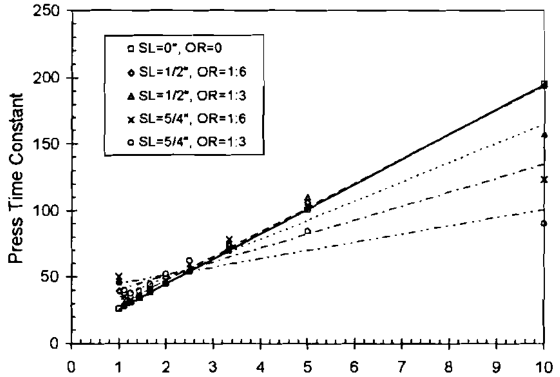

Figure 6. Effect of vibrator oscillation on the relationship between press time constant and image coverage for the 100-0-0 inker.

The press time constant is slightly smaller for the 60-20-20 inker than the 100-0-0 inker under all of the oscillation conditions investigated in this study. The faster response of the former inker to a step change in the ink feedrate can be ascribed to its multiple ink delivery paths and to the less bulky inker volume. Oscillation of vibrators apparently does not alter these facts.

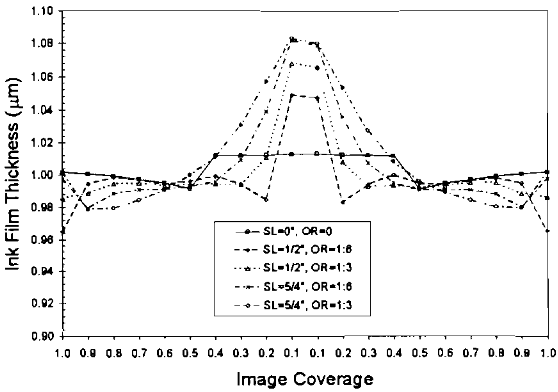

Figure 7. Steady-state ink film thickness of the bar graph shown in Figure 3 produced by the 100-0-0 inker under various oscillation conditions.

Mean Ink Residence Time

MacPhee et al. (1986) defined the mean ink residence time as the ratio of the ink volume in the inker to the ink throughput rate. It is a measure of the time that the ink spends on the rollers. The mean ink residence time was also found to be inversely proportional to the image coverage in the absence of vibrator oscillation (Chou and Bain, 1996). That is, the ink spends much more time on the inking rollers for light coverage formes and hence tends to emulsify too much water on the sheetfed press or to tack up on the web press, making it very difficult to print those formes (MacPhee et al., 1986).

As the ink residence time is critical to the operation of lithographic printing process, it is important to determine if the oscillation of vibrator affects the mean ink residence time. Tables 4 and 5 summarize the mean ink residence time as a function of image coverage for the 100-0-0 and 60-20-20 inkers, respectively. The linear regression coefficients, R^2, of the mean ink residence time versus the reciprocal of image coverage are also listed. It is a surprise to learn that oscillation does not affect the mean ink residence time at all. The mean ink residence time remains a perfect linear relationship with the reciprocal of image coverage, as indicated by R^2. A reasonable explanation to this behavior is as follows. The lateral flow of ink causes changes in both ink volume in the inker and ink throughput rate in such a way that they balance each other and the effect of vibrator oscillation on the mean ink residence time vanishes.

Table 4. Mean ink residence time as a function of image coverage for 100-0-0 inker.

SL OR	0" 0	1/2" 1:6	1/2" 1:3	5/4" 1:6	5/4" 1:3
0.1	203.17	202.95	203.03	202.98	203.71
0.2	108.29	108.29	108.21	108.05	108.12
0.3	76.78	76.83	76.82	76.71	76.62
0.4	61.02	61.09	61.08	61.05	60.93
0.5	51.47	51.42	51.42	51.41	51.36
0.6	45.20	45.20	45.19	45.20	45.17
0.7	40.67	40.67	40.69	40.70	40.74
0.8	37.27	37.26	37.30	37.32	37.36
0.9	34.60	34.63	34.65	34.67	34.42
1.0	32.45	32.05	31.71	31.35	30.94
R^2	1.0000	1.0000	1.0000	0.9999	0.9999

Table 5. Mean ink residence time as a function of image coverage for 60-20-20 inker.

SL OR	0" 0	1/2" 1:6	1/2" 1:3	5/4" 1:6	5/4" 1:3
0.1	196.51	196.50	196.56	196.51	196.71
0.2	101.71	101.76	101.76	101.72	101.78
0.3	70.30	70.33	70.34	70.33	70.31
0.4	54.54	54.57	54.58	54.57	54.55
0.5	45.15	45.13	45.13	45.13	45.10
0.6	39.01	39.01	39.01	39.01	38.99
0.7	34.65	34.65	34.65	34.65	34.66
0.8	31.35	31.35	31.35	31.36	31.37
0.9	28.77	28.78	28.78	28.79	28.78
1.0	26.71	26.71	26.68	26.64	26.63
R^2	1.0000	1.0000	1.0000	1.0000	1.0000

It has been shown that in the absence of vibrator oscillation the press time constant is inversely proportional to the image coverage and the thickness of ink film printed on the substrate is uniform across the press under the operation conditions that the ink feedrate is set in proportion to the image coverage of each printing zone. This relationship is disturbed in the real world by the oscillation of vibrators which causes a lateral flow of ink from high to low image coverage zones. Hence, the proportionality relationship between ink throughput rate and image coverage in each column no longer exists. An important inference can be drawn from the relationship between mean ink residence time and image coverage. If the ink keys can be so adjusted that the actual ink throughput rate, instead of ink feedrate, in each column is proportional to the columnar image coverage, the press time constant should remain inversely proportional to the image coverage of the plate and the oscillation of vibrators should not affect this relationship. The printed ink film should be also uniform across the press. Proof of this inference is nevertheless beyond the scope of this paper.

Ink Flow Ratios

As the ink passes through the nip between form roller and plate cylinder, a portion of ink is taken away by the image area of the plate, resulting in a reversed image on the form roller. Because the diameter of form rollers is generally smaller than that of plate cylinder, the reversed image on the form roller overlaps subsequently with another part of the plate image and gives rise to the so-called ghost on the printed sheet. The ghost images residing on the first, second, and third form rollers of both 100-0-0 and 60-20-20 inkers have to travel through 7, 5, and 4 nips to reach the substrate, respectively. Every time it passes through a nip, its magnitude is halved as a result of the 50/50 film-splitting assumption. So, the magnitude of ghost can be minimized, if the majority of ink is contributed to the plate by the first form roller. It has been shown in the first paper (Chou and Bain, 1996) that the first form roller of the 100-0-0 inker contributes the majority of ink to the plate and the contributions from the second and third form rollers are substantially less. The 100-0-0 inker therefore tends to produce an ink film more uniform than the 60-20-20 inker. It was then concluded that the major function of the second and third form rollers of the 100-0-0 inker is to smooth out the ink film laid down on the plate by the first form roller.

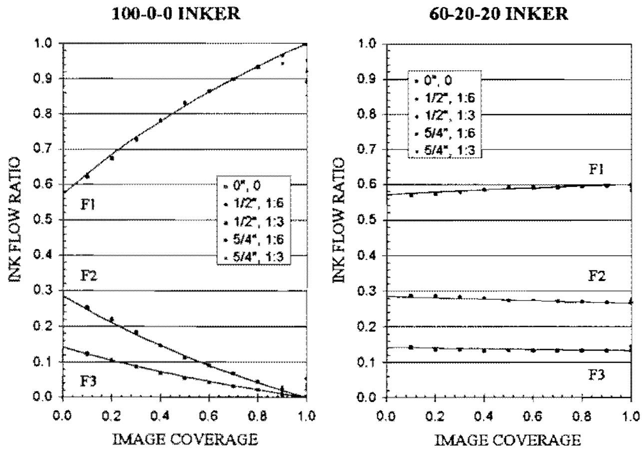

Figure 8. Effect of vibrator oscillation on the ink flow ratios of both 100-0-0 and 60-20-20 inkers as a function of image coverage.

The relative contribution of ink to the plate from each form roller is measured by the ink flow ratio. Figure 8 illustrates the effects of vibrator oscillation and image coverage on the ink flow ratios of both 100-0-0 and 60-20-20 inkers. The data obtained under various oscillation conditions essentially overlap one another at each image coverage, except the 100% coverage. Those data are also in excellent agreement with the theoretical values predicted by Guerrette (1985), as shown by the lines drawn through the data in the charts. These results indicate that the oscillation of vibrators does not have any significant effect on the ink flow ratios of both inkers.

Lateral Flow of Ink

Another series of simulation experiments were designed to investigate the effect of oscillation conditions on the extent of lateral flow of ink. It was assumed that the entire plate was covered with a uniform image of solid, 75%-tine, 50%-tint, or 25%-tint. Only the center ink key was opened to such a setting that an ink film of 1 μm thick would be printed on the substrate in the absence of vibrator oscillation. The rest of keys was closed completely.

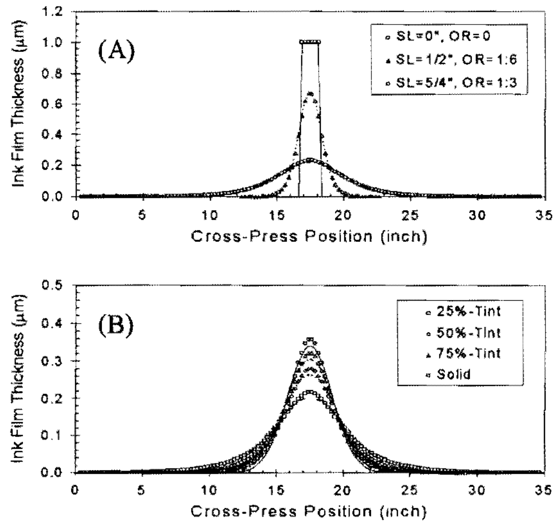

Figure 9. Effects of (A) vibrator oscillation and (B) image coverage of the plate on the extent of lateral flow of inks.

Figure 9A illustrates the effect of vibrator oscillation on the distribution of ink film across the press of the 100-0-0 inker. A step distribution curve was obtained when the vibrators were silenced. In comparison, a bell-shaped distribution curve was obtained when the vibrators oscillated. The peak height decreased and the width increased with increasing magnitude of vibrator oscillation. These results indicate that the more vigorous the oscillation of vibrators, the more ink flows laterally and the further away it reaches.

It is expected that the throughput rate of ink in a specific inking zone should increase with increasing image coverage of the plate and hence the quantity of ink flowing laterally would be reduced substantially. This phenomenon is clearly demonstrated by the distribution of ink film across the press of the 100-0-0 inker as a function of image coverage (Figure 9B) under the oscillation conditions of 5/4" stroke length and 1:6 oscillation rate. The peak height decreases and the width increases with decreasing image coverage.

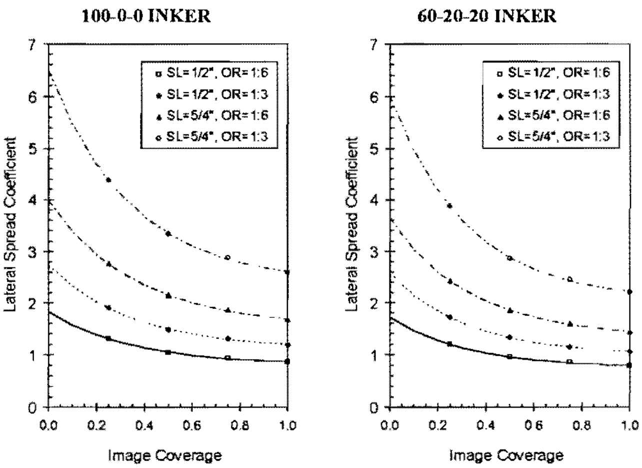

Figure 10. Effects of vibrator oscillation and image coverage on the lateral spread coefficient.

Because the distribution of ink film thickness across the press exhibits a bell-shaped curve, an equation similar to the normal distribution equation was used to express the extent of lateral flow of ink.

$$H = H_m \exp\left[- \frac{(X - X_o)^2}{2\sigma^2} \right] \tag{8}$$

with,

H : thickness of ink film printed on the substrate,
H_m : maximum thickness of printed ink film,

X : the position across the press,
X_o : the center of the specific inking zone,
σ : lateral spread coefficient, which is equivalent to the standard deviation of the normal distribution.

Figure 10 summarizes the effect of vibrator oscillation on the lateral flow of ink for 100-0-0 and 60-20-20 inkers. These charts indicate that the lateral spread coefficient decreases exponentially with increasing image coverage. The more vigorous the oscillation of vibrators, the larger the lateral spread coefficient. The stroke length is more effective than the oscillation rate. That is, the extent of lateral flow of ink increases with increasing magnitude of vibrator oscillation and with decreasing image coverage of the plate. The 100-0-0 inker also tends to spread the ink slightly more wider than the 60-20-20 inker, probably due to the slightly bulkier ink volume of the former inker.

Print Quality

An ideal inker should be able to deliver a uniform ink film to the plate regardless of the image layout of the plate. In reality, the ink film laid down on the plate by an offset inker is never uniform. Most of the ink film thickness variations result from improper setting of ink keys, which is presumably easy to correct. However, there are two image-related variations of ink film thickness that cannot be compensated by ink key adjustment, namely, ghosting and starvation. Image-related ghost has been discussed previously. The gap of the plate cylinder can also cause a variation of ink film thickness in a way similar to ghosting. So, ghosting is an ink film thickness variation in the printing direction and in many cases can be concealed with a proper layout of images. The magnitude of ghost can be significantly reduced by multiple ink form rollers of different diameters, as commonly practiced by press manufacturers. If the diameters of ink form rollers are the same, ghosting is augmented instead.

When the forme has large L-shaped solids or solid frames with large open areas in them, the vertical solids use more ink and hence print lighter than the horizontal bars which consume much less ink. This variation of ink film thickness in the cross-press direction is generally referred to as starvation. Starvation has nothing to do with the relative sizes of ink form rollers, because the sides of images on multiple form rollers always register with one another. It will become clear later in this paper that starvation is better treated of as a different print quality attribute from ghosting, though it is often taken as a special case of ghosting in the literature (Hull, 1968; Prince, 1988; and MacPhee, 1992). The magnitude of starvation can be reduced by a leveling action of ink distribution across the press due to the oscillation of vibrators or by a better means of feeding ink into the areas which need ink (Hull, 1968).

The T-bar test form illustrated schematically in Figure 11 was designed specifically for evaluating the magnitudes of ghost and starvation produced by the inkers in this study. It is so designed that the memory of the thin horizontal bar carried by the form roller

F1, F2, and F3 is transferred to the thick horizontal block to produce ghost images as indicated by F1, F2, and F3, respectively. The memory-free image on the horizontal block indicated by BS is used as the baseline for calculating the percentage ghost. The normal and inverted T-bar arrangements make it possible to determine the effect of image layout on the magnitude of ghost. The center line of the vertical bar aligns with the interstice between two ink keys so that an abrupt change in the image coverage occurs in both inking zones. A ditch and ridge pattern of the printed T-bar image, as shown in Figure 12, is common to all inkers equipped with keyed ink input devices. This ridge disappears when printed with a keyless inker (Chou, et al., 1996).

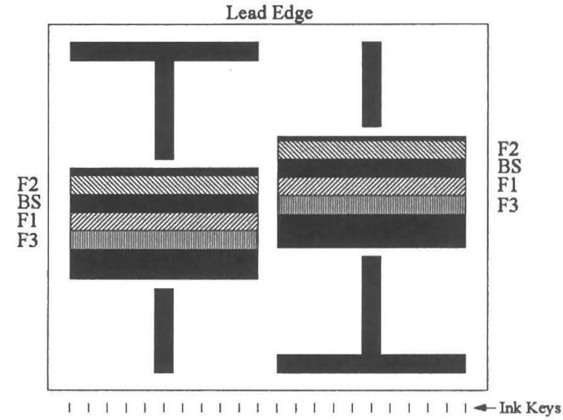

Figure 11. T-bar graph used as the test form to appraise print quality attributes produced by an inker.

Ghosting

Close examination of Figure 12 reveals a ripple appearance on the thick horizontal block in the printing direction. The troughs are ghost images of the thin horizontal bars resulting from three ink form rollers. The magnitude of ghost is calculated by the following equation,

$$G = \left[1 - \frac{H_{Fi}}{H_{BS}} \right] * 100 \tag{9}$$

with,

G : percentage ghost,
H_{Fi} : ink film thickness of ghost image produced by the form roller Fi,
H_{BS} : ink film thickness of the baseline image.

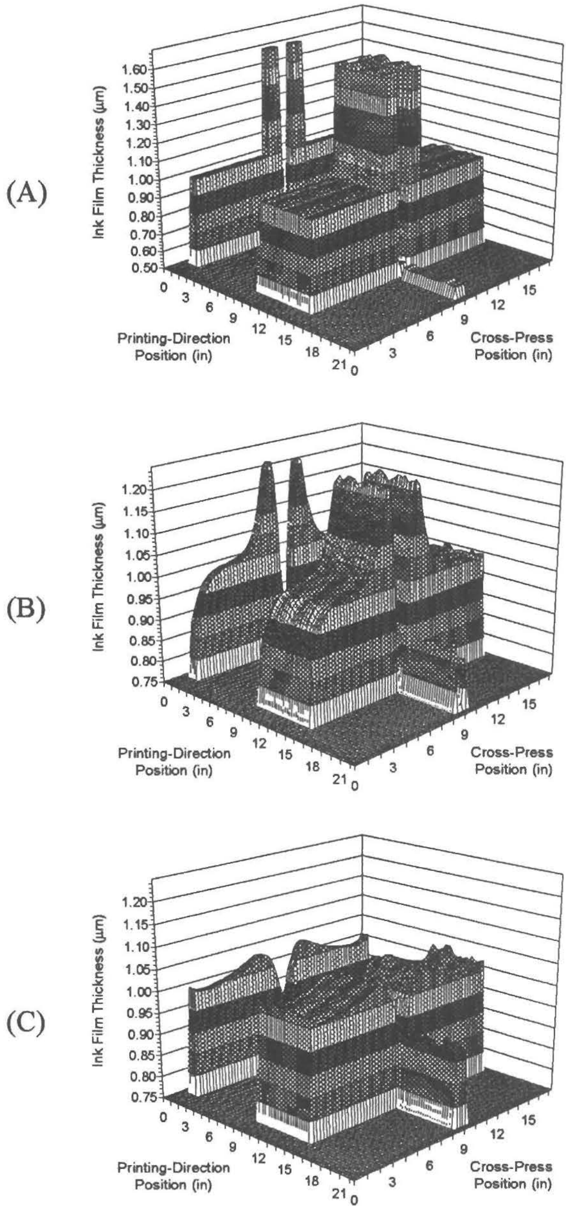

Figure 12. 3-D column charts of the T-bar image obtained from the 100-0-0 inker after 520 plate cylinder revolutions under oscillation conditions of (A) vibrators silenced, (B) SL=1/2", OR=1:6, (C) SL=5/4", OR=1:3.

If the ink film thickness of the ghost image is the same as that of the baseline, ghost will not exist and the percentage ghost calculated according to Eq. (9) is 0. The steady-state ink film thicknesses derived from Eq. (7) are used to calculate the percentage ghost. Tables 6 and 7 list the percentage ghost data obtained under various oscillation conditions for the 100-0-0 and 60-20-20 inkers, respectively. Because the oscillation of vibrators causes a flow of ink only in the cross-press direction, it should not affect the distribution of ink in the printing direction. So, it is not a surprise to observe that the oscillation of vibrators has a negligible effect on the magnitude of ghost.

The ghost produced by the 100-0-0 inker is slightly less than that by the 60-20-20 inker. This observation is consistent with the predictions made in the first paper and hereinbefore. The major function of the second and third ink form rollers is to smooth out the ink laid down on the plate by the first form roller of the 100-0-0 inker. In comparison, the second and third form rollers of the 60-20-20 inker contribute a significant portion of ink to the plate. The normal T-bar produces slightly less ghosting than the inverted T-bar for both inkers, indicating that the layout of heavy coverage in the trailing edge may be preferred.

Table 6. Effect of vibrator oscillation on percentage ghost and starvation of the T-bar image for the 100-0-0 inker.

Stroke	Osc.	T-Bar				Inverted T-Bar			
Length	Rate	G(F1)	G(F2)	G(F3)	S	G(F1)	G(F2)	G(F3)	S
0"	0	1.33	1.13	0.68	65.04	1.50	1.40	0.81	65.01
1/2"	1:6	1.34	1.11	0.66	18.20	1.49	1.39	0.77	18.34
1/2"	1:3	1.32	1.11	0.64	8.69	1.51	1.32	0.80	8.46
5/4"	1:6	1.34	1.07	0.69	5.00	1.49	1.34	0.81	5.09
5/4"	1:3	1.33	1.07	0.70	2.24	1.48	1.30	0.83	2.35

Table 7. Effect of vibrator oscillation on percentage ghost and starvation of the T-bar image for the 60-20-20 inker.

Stroke	Osc.	T-Bar				Inverted T-Bar			
Length	Rate	G(F1)	G(F2)	G(F3)	S	G(F1)	G(F2)	G(F3)	S
0"	0	1.38	1.55	1.57	64.95	1.41	1.74	1.65	64.91
1/2"	1:6	1.38	1.55	1.54	19.27	1.39	1.75	1.61	19.39
1/2"	1:3	1.34	1.56	1.50	10.38	1.40	1.70	1.63	10.12
5/4"	1:6	1.36	1.52	1.53	6.29	1.37	1.73	1.60	6.26
5/4"	1:3	1.34	1.53	1.53	3.76	1.36	1.70	1.60	3.64

Starvation

The ridge and ditch pattern shown in Figure 12 is typical of the T-bar image produced by any conventional keyed inker. In the absence of vibrator oscillation, the ridge is very high and the ditch is very deep (Figure 12A). Besides, the horizontal bar and block are both very flat in the cross-press direction. The oscillation of vibrators causes the ink to flow laterally, resulting in the falling ridge, rising ditch, and declining horizontal bar and block (Figure 12B). The more rigorous the oscillation of vibrators, the less difference in the ink film thicknesses of ridge and ditch and the less steep the horizontal bar and block (Figure 12C). These charts indicate that the leveling action increases with the magnitude of vibrator oscillation.

The percentage starvation can be calculated by the following equation,

$$S = \left[1 - \frac{H_D}{H_R} \right] * 100 \tag{10}$$

with,

S : percentage starvation,
H_D : ink film thickness of the ditch,
H_R : ink film thickness of the ridge.

If the ink film thickness of the ridge is the same as that of the ditch, the starvation disappears and the percentage starvation calculated according to Eq. (10) is 0. The starvation data, also listed in Tables 6 and 7, were calculated from the steady-state ink film thicknesses of ridge and ditch. These results show that the effect of vibrator oscillation on starvation is remarkable; the stroke length is more effective in reducing starvation than the oscillation rate; and the 100-0-0 inker produces less starvation than the 60-20-20 inker. These findings are consistent with those in the study of lateral flow of ink, indicating that the starvation is controlled by the oscillation of vibrators.

Application To Printing Process Control

The gap space between fountain blade and fountain roller is generally set by ink keys in such a way that the gap space or the ink feedrate in each inking zone is proportional to the image coverage of that zone. A relatively uniform ink film across the forme can be easily achieved, if the image coverage of the plate is also relatively uniform across the press, e.g. pages containing only text. For pages with a considerable amount of graphic works, the ink key setting may vary significantly across the press. Even for the modern open fountain with discrete ink keys or digital injector, of which the adjustment of an ink key will not affect the setting of neighboring keys, the oscillation of vibrators still causes a lateral flow of ink from high to low image coverage zones and hence alters the ink throughput rate in each zone. That is, the ink throughput rate is different from the ink feedrate. The printed ink film in the high coverage zones is therefore thinner than that in the low coverage zones. So, this lateral flow of ink caused by the oscillation of vibrators must be taken into account when setting ink keys. In other words, the gap space corresponding to high coverage zones must be larger than and that of low coverage zones must be smaller than the spaces set in proportion to the image coverage.

It has been shown that the amount and distance of ink traveling laterally depends strongly on the extent of oscillation. The larger the stroke length and/or the faster the oscillation rate, the more ink flows from high to low coverage zones and the further away it reaches. Even with a fixed set of oscillation conditions, the lateral flow of ink also varies with the image coverage of neighboring inking zones. The lighter the image coverage, the greater extent the lateral flow of ink. These variables make it very difficult for a pressman to manually set ink keys to achieve an even ink film laid down on the plate. However, it is not so difficult to implement a computer algorithm in the press control to compensate the lateral flow of ink caused by the oscillation of vibrators. The discussion of this algorithm is beyond the scope of this paper.

Conclusions

The oscillation of vibrators is essential to prevent the formation of ink ridges on the inking rollers, which will results in very uneven distribution of ink across the press. The action of vibrator oscillation causes a lateral flow of ink from high to low image coverage zones, i.e., a leveling action of ink distribution across the press. This lateral flow of ink is very important in reducing the magnitude of starvation due to an abrupt change in the image coverage of the forme. However, it complicates the operation of setting ink fountain keys. The simple proportionality relationship between image coverage and ink feedrate at each inking zone is disturbed. A more advanced press control system is required to compensate the lateral flow of ink in order to deliver an ink film to the plate that is uniform across the press.

The extent of lateral flow of ink or the leveling action across the press depends on the magnitude of vibrator oscillation and the image coverage of the plate. The more severe the oscillation of vibrators and/or the lighter the image coverage of the plate, the greater extent the ink flows laterally away from the ink input zone. The magnitude of vibrator oscillation increases with increasing stroke length and oscillation rate, and the stroke length is more effective than the oscillation rate.

The oscillation of vibrators has a dramatic effect on the magnitude of starvation, but its effect on the magnitude of ghost and the ink flow ratio of form rollers is negligible. It alters the actual ink throughput rate at each inking zone and hence changes the press time constant of that zone. The linear relationship between press time constant and the reciprocal of image coverage is disturbed by the oscillation of vibrators. However, the linear relationship between mean ink residence time and the reciprocal of image coverage is not affected by the oscillation action at all. The inference is that if the ink feedrate is so adjusted to compensate the lateral flow of ink that the actual ink throughput rate is proportional to the image coverage of each inking zone, the linear relationship between press time constant and the reciprocal of image coverage will be restored.

The 100-0-0 inker tends to produce prints of higher quality than the 60-20-20 inker does, i.e., less ghost and less starvation. The magnitude of ghost is related to the ink flow ratio. The more ink contributed from the first form roller to the plate, the less ghost the inker will produce. It is concluded that the major function of the second and third form rollers of the 100-0-0 inker is to smooth out the ink film laid down on the plate by the first form roller. The magnitude of starvation is probably related to the ink volume of inkers. The larger the ink volume, the greater the buffering action of the inker and hence the less starvation it will produce. On the other hand, the 100-0-0 inker tends to respond to a change of ink feedrate slightly more slowly than the 60-20-20 inker does. This slow response is ascribed to the single ink delivery path and slightly bulkier ink volume of the 100-0-0 inker. The oscillation of vibrators does not affect those performance characteristics of the two inkers.

Corrections

Equations for calculating percentage ghost and starvation presented as Eqs. (4) and (5) in the previous paper (Chou, et al., 1996) are incorrect. They should be replaced by Eqs. (9) and (10) of this paper.

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