# A RELATIVELY SIMPLE METHOD FOR CALCULATING THE DYNAMIC BEHAVIOR OF INKING SYSTEMS

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Abstract: A method, using a common spreadsheet program, is described for calculating the dynamic behavior of inking systems during quasi steady state and in response to changes in ink feed over time. The model used can account for changes in plate coverage in the direction around-the-cylinder, but not across-the-cylinder. Comparisons with experimental results demonstrate the validity of the method and examples are presented to illustrate its capabilities.

## Introduction

The factors that affect the dynamic behavior of inking systems are of great interest to both the designers and users of printing presses. Variations in ink film thicknesses throughout the roller train over relatively short times are of interest in predicting unwanted print density variations due, for example, to the gap in the plate cylinder. Long term variations are of interest in learning how quickly the inking system responds to operator adjustments to ink feedrate. Quick response to operator adjustments is, of course, desirable to reduce make-ready time and waste. In this context, time is measured in terms of plate cylinder revolutions. Thus a short time corresponds to a few plate cylinder revolutions, while long times correspond to tens of revolutions.

The method of calculation described in this paper is akin to Finite Element Analysis in that dynamic response is represented by the results of sets of sequential steady-state calculations carried out at small, equal,

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increments of time. This overall approach is not new, as descriptions of it can be found dating back over twenty years (Scheuter and Rech, 1970). What is thought to be new is the specific modeling and the use of a standard spreadsheet program and a desk top computer, thus making it relatively easy and quick to carry out the calculations.

The main body of this paper consists of three sections that contain background information, a detailed description of the method, and sample calculations. A discussion of the results and some conclusions are given in the last section.

## Background Information

Two types of dynamic behavior are of interest: short term and long term. Short term behavior concerns the response of printed ink film thickness under quasi steady state conditions, where the only disturbances are periodic ones produced within the press. Examples of such disturbances are the action of the ink ductor roller and the gap in the plate cylinder.

A limited number of measurements of long term dynamic behavior have been made (Mill, 1961 and Neuman and Almendinger, 1979) and these have demonstrated that the time-dependent relationship between print density (and/or printed ink film thickness) and ink feedrate can be described by a first order differential equation of the form:

$$\tau \frac{dH}{dt} = C_1 F - H \qquad (1)$$

where:

$C_1$ = a constant
F = ink feedrate
H = printed ink film thickness
t = time
$\tau$ = system time constant

Accordingly, for a step change in feedrate from $F_0$ to $F_1$ at time zero, the response of ink film thickness with respect to time will be in accordance with equation (2) as follows:

$$H = H_0 + \Delta H\left(1 - e^{-t/\tau}\right) \qquad (2)$$

where:

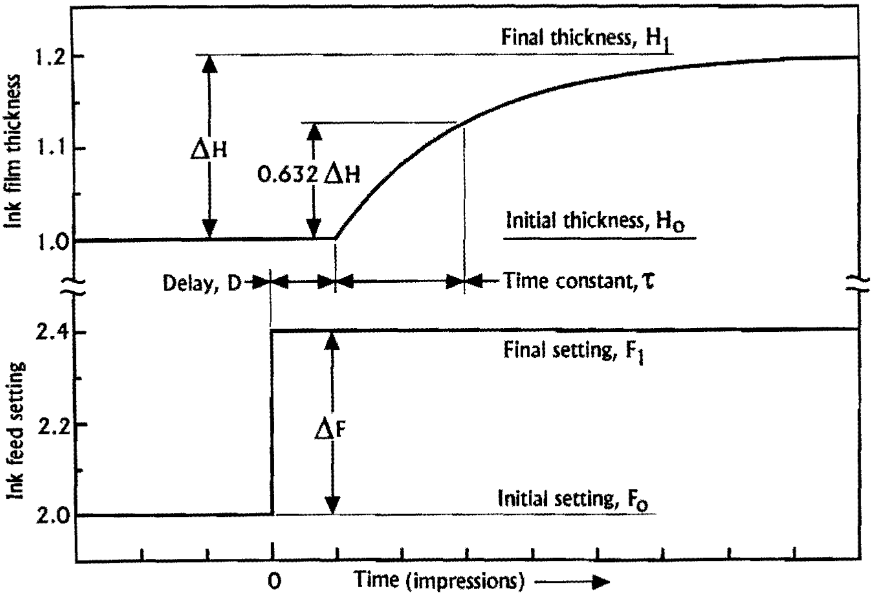


Figure 1 Response of ink film thickness to step change in feed setting at time zero.

$H_o$ = film thickness at t = 0
$\Delta H$ = change in ink film thickness at equilibrium after ink feedrate has been changed from $F_o$ to $F_1$.

The actual behavior, as measured by Neuman and Almendinger, includes a delay, D, between time zero when feedrate is changed, and the time when a change in printed ink film thickness (i.e. print density) is first observed. This typical behavior, illustrated in Figure 1, is commonly referred to as an exponential response wherein the output variable (in this case printed ink film thickness) gradually approaches its final value, $H_1$ on an exponential curve. The system time constant, $\tau$, is of importance because it determines how rapidly the final value is approached. For example, the output variable will change by 63.2% of the final change, $\Delta H$, in a time equal to one time constant and by 95% in three time constants. In printing, the significance of this is that printed sheets are wasted during the time required to reach equilibrium following a change in ink feed. Thus, short system time constants are desirable.

In his experimental work, Mill showed that system response time increases as ink coverage on the plate decreases. In addition, he developed a method for predicting the relationship on a given press but his method is not easy to implement. Subsequently, it was suggested that mean ink residence time, which is easy to calculate, could serve as a stand-in for the time constant (MacPhee, Kolesar, and Federgun, 1985).

The method described here can be used to assess both types of behavior, as will be shown by the examples presented.

## Description of the Method

The method is based on three presumptions that are explained as follows:

1. The dynamic response of the ink film thicknesses throughout the ink roller train and printing cylinders can be represented by the results of sets of sequential steady state calculations that are carried out at small equal intervals of time. In each such set of steady state calculations, the film thicknesses at the exit of each nip in the system are calculated, assuming conservation of volume, i.e. that outflow from the nip is equal to inflow at that instant. This basic relationship was described many years ago (Hull, 1968) and subsequently expanded (Guerrette, 1985) to include coverages other than solid or one hundred percent and film splitting ratios of other than 50:50. The film thicknesses at the nip entrances are taken as being equal to the exit thickness of the corresponding upstream nip at some previous instant in time, corresponding to the travel time between nips. For example, at any given instant in time, the ink film thicknesses at the exit of Nip 5 between Rollers A and E in Figure 2, can be expressed by equation (3) as follows, assuming a 50:50 film split:

$$2h_1(t_n) = h_2(t_n - \Delta t_{65}) + h_w(t_n - \Delta t_{15}) \qquad (3)$$

where:

film thicknesses, h, are defined in Figure 2
$t_n$ = given instant of time
$\Delta t_{65}$ = travel time of roller E from Nip 6 to Nip 5
$\Delta t_{15}$ = travel time of roller A from Nip 1 to Nip 5

For nips involving a roller and the plate cylinder, two equations are needed to account for changes in ink coverage on the plate. For example, the ink film thicknesses at the exit of Nip 1 in Figure 2 are expressed by equations (4) and (5) as follows:

$$h_w(t_n) = \left(1 - \frac{x}{2}\right) \bullet h_1(t_n - \Delta t_{51}) + \left(\frac{1}{2}\right) \bullet h_b(t_n - \Delta t_{b1}) \qquad (4)$$

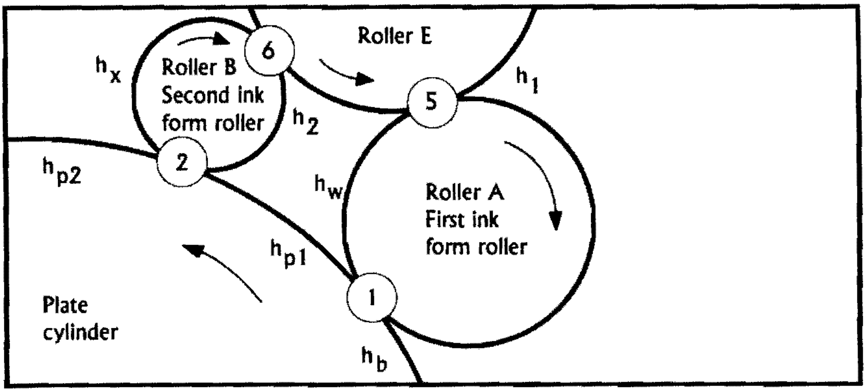


Figure 2 Identification of nips and films described in equations (3) to (5).

$$h_{p1}(t_n) = \left(\frac{1}{2}\right) \bullet h_b(t_n - \Delta t_{b1}) + \left(\frac{x}{2}\right) \bullet h_1(t_n - \Delta t_{51}) \qquad (5)$$

where:

x = fractional plate coverage (e.g. 1.0 for solid, 0.5 for 50% screen, and zero for no image.
$\Delta t_{51}$ = travel time of roller A from Nip 5 to Nip 1
$\Delta t_{b1}$ = travel time of plate cylinder from Nip b to Nip 1

The interval of time between each set of sequential steady state calculations must thus correspond to some unit circumferential travel time of a point on a roller or cylinder.

2. The circumferential distance between all nips can be approximated by a multiple of the unit length of travel, which of course is related to the unit circumferential travel time.

3. The circumferences of all rollers and cylinders can be approximated by some multiple of the unit length. In practice it has been found that good results are obtained when the plate cylinder circumference is divided into 16 to 18 unit lengths or segments. The roller circumferences generally will then fall in the range of 3 to 8 unit lengths, and nip to nip travel lengths in the range of 1 to 4 unit lengths.

If the interval between each set of steady state calculations is looked upon as a unit length of travel, rather than a unit travel time, the independent variable can be converted directly to units of plate cylinder revolution; thereby enabling the results to be expressed as functions of plate cylinder revolutions or impressions. Thus the results are independent of press speed.

There is a very important implication to the implementation of these presumptions. This is that the roller-cylinder layout used in the calculations will not be an exact replica of the press under study. This, of course, is due to the changes that must be made in the diameters and nip-to-nip distances to satisfy presumptions 2 and 3 above. The major practical problem that arises as a consequence is that the calculated magnitude of spot ghosting may be greater than actual because some of the form rollers may have to be made commensurate, i.e. have the same diameter.

One very positive feature of this model is that plate cylinder coverage need not be constant in the around-the-cylinder direction, because each segment of plate cylinder can have a unique coverage ranging from zero to 1.0.

When this model is utilized, the task of calculating dynamic response is reduced to a series of sequential tasks wherein each sequential task consists of solving a group of simultaneous equations. Although the individual equations are quite simple, the overall job would be intimidating if it had to be carried out manually because of the large number of calculations required. Typically, over twenty simultaneous equations must be solved at each interval while the number of intervals required can easily reach 5000. Thus over 100,000 calculations may be necessary to produce an answer to a single problem. For film splits other than 50:50, the number of calculations will be almost doubled. Fortunately, the calculations can be carried out very quickly on a personal computer using any one of a number of currently available spreadsheet programs. The results presented here were obtained using a 486 personal computer, and the spreadsheet program Excel (Microsoft, 1992). The heart of this program is a table or spreadsheet that can contain as many as 256 columns, identified by letters, and 16,384 lines or rows, numbered in sequence. The intersection of a column and a row is referred to as a cell. A cell may contain a fixed number or an instruction (an equation) to calculate a given variable. In utilizing the program for these calculations the overall concept is to have each row represent a discrete sequential time (or sequential travel), while columns are assigned to specific nips. (The first two columns are used to identify the time sequence and coverage of the plate cylinder segment entering the nip formed by contact with the first ink form roller.) The last nip in the chain, blanket to paper, is assigned to the last column on the right while the first nip at the head of the roller train is assigned the first nip column on the left. This method is capable of simulating a press with either a constant ink feed or a discontinuous ink feed by a ductor roller.

| | A | B | | R | S | T |
|---|---|---|---|---|---|---|
| 1 | Time, t | Coverage, x | | $h_1$ | $h_2$ | $h_w$ |
| 2 | -2 | | | 0 | 0 | 0 |
| 3 | -1 | | | 0 | 0 | 0 |
| 4 | 0 | 1.0 | | 0 | 0 | 0 |
| 5 | Equation A | 1.0 | | Equation R | Equation S | Equation T |
| 6 | Equation A | 1.0 | | Equation R | Equation S | Equation T |
| 7 | Equation A | 1.0 | | Equation R | Equation S | Equation T |
| 8 | Equation A | 1.0 | | Equation R | Equation S | Equation T |
| 9 | Equation A | 1.0 | | Equation R | Equation S | Equation T |

Figure 3 Layout of spreadsheet for calculating dynamic response. For the example in the text, equation (R) would correspond to equation (3) and equation (A) would advance time in each succeeding cell by one unit. The values of $h_2$ and $h_w$, required in equation (R), would be taken from the appropriate preceding cells in columns S and T.

The equations governing each nip are entered into assigned columns such that the calculation of film thickness in a given nip is performed sequentially in each cell in the column to which it is assigned. This is illustrated in Figure 3. The input film thicknesses required in each cell calculation are automatically read from the appropriate cells in preceding rows. The computation of dynamic response for a given set of conditions proceeds from zero time through as many time intervals as specified. The entire computation takes but a few seconds once the problem has been set up or entered into the spreadsheet program. Setup time, however, can range from a few minutes for minor changes to existing computations to hours or days for a completely new problem.

## Sample Calculations

As a means of checking the validity of the method, sample calculations were made of both long-term and short-term behavior. The former comprised calculations of the response of the press used in the experiments by Neuman and Almendinger, referred to above. The first experiment selected for comparison was the response of print density to a step increase in ink feedrate. The experiments of Neuman and

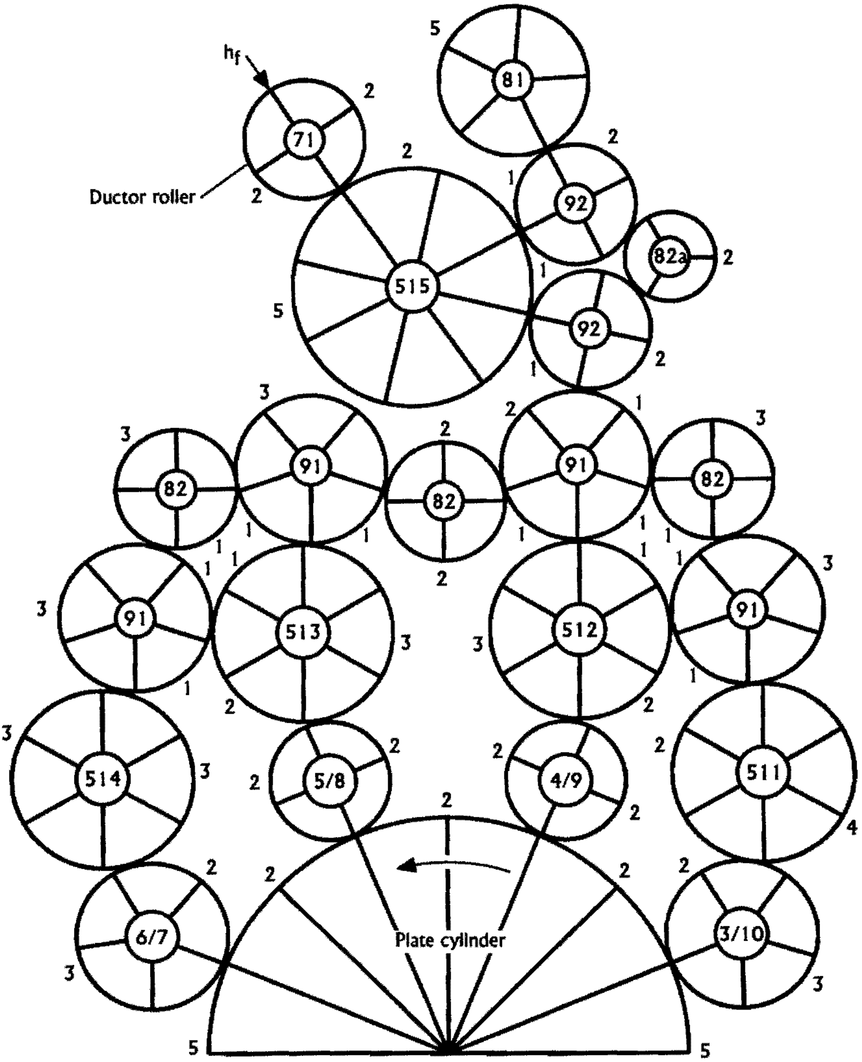


Figure 4  Roller diagram of press used by Neuman and Almendinger. Spokes indicate roller circumference in unit lengths. Numbers outside rollers are assumed path lengths used in the sample calculations. Inside numbers identify rollers.

Almendinger were carried out on a Series 108 single-color Roland Favorite sheetfed press using a form with a plate coverage of 25 percent. Figure 4 is a roller diagram of this press.

For the calculation model, the plate cylinder circumference was divided into 16 equal segments of unit length. Consequently, the roller circumferences were adjusted to circumferences of either 3, 4, 5, 6, or 8 unit lengths. Table I is a comparison of the actual roller diameters and circumferences with those used in the calculation. In Figure 4, it can be seen that very few of the actual nip-to-nip distances are some multiple of the unit length. The numbers outside the rollers give the assumed number of unit lengths used for these distances in the calculations.

Table I Comparison of actual roller sizes with sizes used in model. Data shows that the difference between total roller circumference, and hence storage capacity, is about 4 percent.

| Roller ID | Quan. | Diameter (inch) | | Circumference (unit length) | | | |
|---|---|---|---|---|---|---|---|
| | | Actual | Model | Actual | | Model | |
| | | | | Roller | Total | Roller | Total |
| 515 | 1 | 4.179 | 4.33 | 7.72 | 7.72 | 8 | 8 |
| 511-4 | 4 | 3.125 | 3.25 | 5.77 | 23.08 | 6 | 24 |
| 92 | 2 | 2.969 | 2.17 | 5.48 | 10.96 | 4 | 8 |
| 91 | 4 | 2.75 | 2.71 | 5.08 | 20.32 | 5 | 20 |
| 82 | 3 | 2.219 | 2.17 | 4.1 | 12.3 | 4 | 12 |
| 82a | 1 | 2.219 | 1.62 | 4.1 | 4.1 | 3 | 3 |
| 81 | 1 | 2.969 | 2.71 | 5.48 | 5.48 | 5 | 5 |
| 71 | 1 | 2.375 | 2.17 | 4.39 | 4.39 | 4 | 4 |
| 6/7 | 1 | 2.75 | 2.71 | 5.08 | 5.08 | 5 | 5 |
| 5/8 | 1 | 2.375 | 2.17 | 4.39 | 4.39 | 4 | 4 |
| 4/9 | 1 | 2.188 | 2.17 | 4.04 | 4.04 | 4 | 4 |
| 3/10 | 1 | 2.563 | 2.71 | 4.73 | 4.73 | 5 | 5 |
| Total | 21 | | | | 106.6 | | 102 |

In the calculation model, the plate cylinder gap is not recognized per se; thus the fractional coverage of the plate must be converted to a fractional cylinder coverage to determine the coverages, x, that must be assigned to each plate segment in the model. For this press, the plate coverage of 25 percent used by Neuman and Almendinger corresponds to a cylinder coverage of 17.7 percent. Accordingly, in the calculation three of the 16 plate segments were assumed to have a coverage of 1.0, while the remaining thirteen were zero, yielding a cylinder coverage of 18.8 percent. Feed by the ductor roller was based on ductor roller measurements made on a similar press that disclosed the following:

| | |
|---|---|
| Ductor cycle: | every other plate cylinder revolution |
| Dwell on roller 515: | one ductor revolution |

Dwell on fountain roller: 1/4 turn of ductor roller (assumed)

It proved relatively straightforward to program these conditions by providing a column in the spreadsheet for specifying the film thickness at the feed-point shown in Figure 4. The equations in the column assigned to the nip between the ductor roller and roller 515 were varied accordingly over a repetitive period of two plate cylinder revolutions to reflect these conditions.

The first calculation carried out was of the response of the printed ink film thickness to a step change in the ink film thickness, $h_f$ at the feed-point, from zero, to the value necessary to produce a nominal steady-state printed film thickness of 1.0. (By successive guesses and calculations a value of 16 was arrived at for $h_f$ to produce a printed film thickness of 1.038.) The calculation required a spreadsheet with thirty-four columns of equations, and took 4096 steps (i.e. rows) for a total of 139,264 individual calculations. As shown by the plotted response in Figure 5, this simulated 256 plate cylinder revolutions. To determine the corresponding values for the time constant, $\tau$, and delay, D, the calculated data was fitted to a modified form of equation (2) that included the delay. The fit was almost perfect, as shown in Figure 5, and yielded a time constant of 85 cylinder revolutions or impressions. This compares very well with the range of 78 - 103 impressions measured by Neuman and Almendinger.

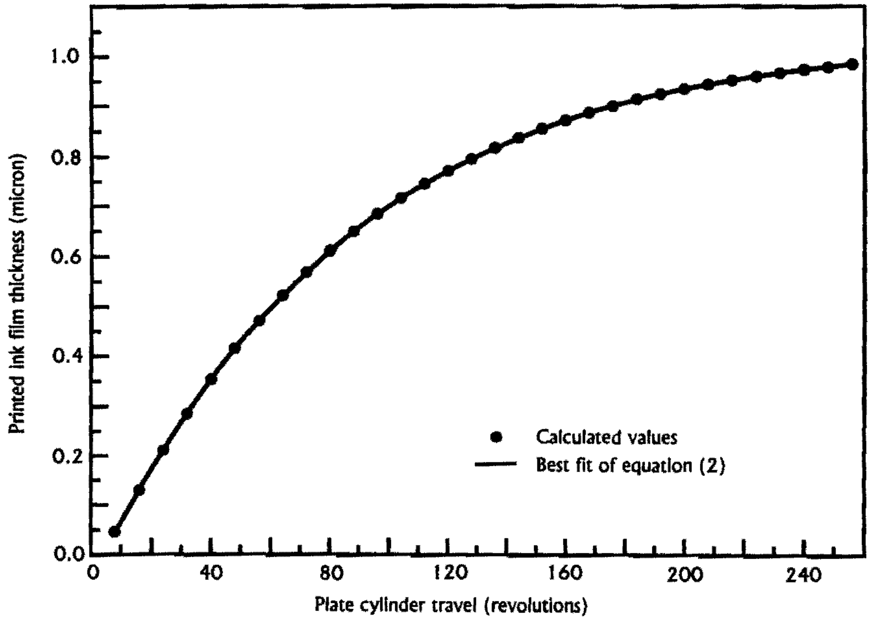


Figure 5 Calculated response to step increase in ink feedrate.

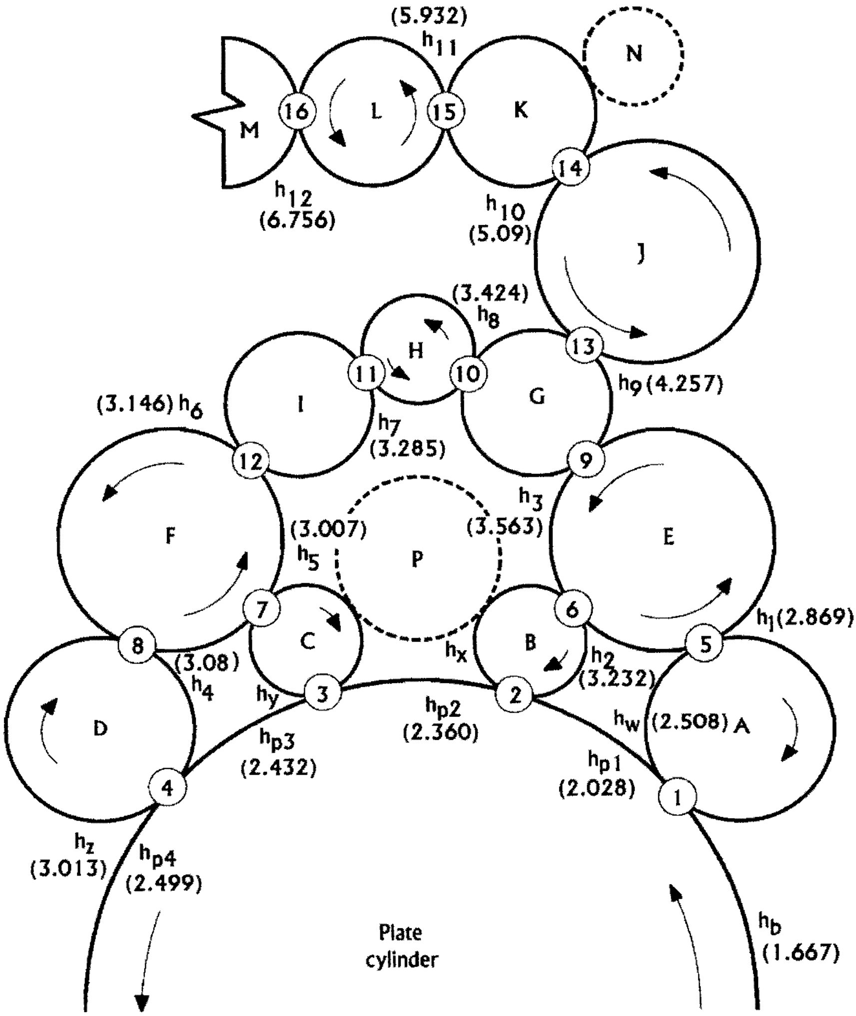


Figure 6 Hypothetical inking system design. Numbers in parentheses are the steady state ink film thicknesses for a printed ink film thickness of 1.0 micron, calculated using the method described by Guerrette (1985). The effect of optional rider rollers N and P was not included. Plate coverage is 100 percent and corresponding cylinder coverage is 83.3 percent.

The calculated value of the delay, D, was 4.5, far less than the corresponding measured values that ranged between 20 and 40 impressions. As a check on the calculated response to a step increase, two additional calculations were made: the response to a step increase assuming no ducting action and a constant feed, i.e. a continuous constant inflow at

$h_F$, and mean residence time. For constant feed, the delay was also 4.5 revolutions, but the time constant was somewhat longer, 104 impressions. The calculated mean residence time, taken as the volume of ink stored on the rollers divided by the volume of ink transferred to the paper per impression, was 106 impressions.

The response to tripping the ink ductor, i.e. a step decrease, was also calculated. This yielded a time constant of 104 impressions and a delay of 4.5 impressions. In this case, the agreement with the measured ranges of 161 - 663 and 0 - 40 impressions respectively, was not very good. The reasons for these differences are discussed in the final section.

One example of the value of this calculation method in assessing short term dynamic behavior is provided by considering the hypothetical inker shown in Figure 6. The quasi steady state ink film thicknesses throughout this configuration were calculated assuming constant ink feed, so as to eliminate disturbances created by the ductor roller. For the case of 100 percent plate coverage, the calculated printed ink film thicknesses are plotted in Figure 7 versus plate cylinder travel. This plot shows the disturbances or ghosts generated by the plate cylinder gap. The worst ghost, generated by commensurate form rollers A and D, has a magnitude of 0.011 micron for a printed ink film thickness of 1.0 micron. This compares very well with the estimate of 0.012 micron obtained using the method employed in the 1985 TAGA paper by Guerrette (Guerrette, 1994).

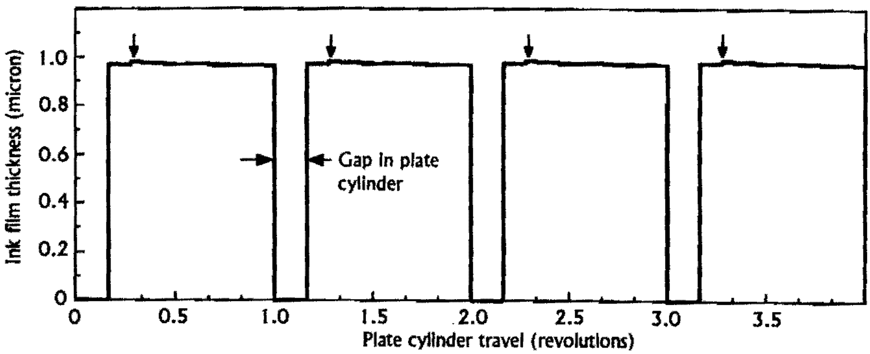


Figure 7 Quasi steady state plot of printed ink film thickness for hypothetical sheetfed press inker shown in Figure 6 for 100 percent plate coverage. Arrows indicate worst ghost produced by presence of plate cylinder gap. Calculated using method described in this paper.

## Discussions and Conclusions

There are three significant features of long term inker behavior that are evident by examining the results of the sample calculations described here, and the experimental results of Neuman and Almendinger, as summarized in Table II.

Table II Comparison of calculated and measured values for the inker design shown in Figure 4. Measured values are from Neuman and Almendinger; calculated values are as described in this paper. The units for all of the listed values are plate cylinder revolutions.

| | Time constant, $\tau$ | | Delay, D | |
|---|---|---|---|---|
| | Meas. | Calc. | Meas. | Calc. |
| Step increase, ductor feed | 78-103 | 85 | 20-40 | 4.5 |
| Step decrease, ductor trip | 161-663 | 104 | 0-40 | 4.5 |
| Step increase, constant feed | --- | 104 | --- | 4.5 |
| Mean residence time | --- | 106 | --- | --- |

The first note of significance is the differences in the various calculated time constants. Three of the calculated time constants are essentially the same (104 - 106 impressions) while the fourth, for the case of a step increase, is almost 20% lower. The explanation of this faster response for a step increase is that the ductor roller feeds more ink to the train at the beginning of the transient because the ink film thickness on the roller it is feeding is less than the equilibrium value. Proof of this is provided by the calculated response for a constant feedrate, and by the calculated mean residence time. This effect that a ductor type feed system has in reducing inker response time to step increases in feedrate is even more pronounced for lighter coverages, as illustrated by the calculated data plotted in Figure 8.

The second important contrast is the difference between the measured and calculated time constants for a step decrease (ductor trip) in ink feedrate. The most plausible explanation for this is that there is a significant amount of dead or imbibed ink on the rollers of an operating press. This dead ink only becomes active, or flows, when there is a change that acts to reduce the volume of ink stored on the rollers, i.e. a decrease in ink feedrate.

The last significant note about the data is the very large difference between the measured and calculated delays. A recent investigation of inker response to the movement of a single ink key (Has, 1993) showed similar delays of 33 impressions or more. The large magnitude of these

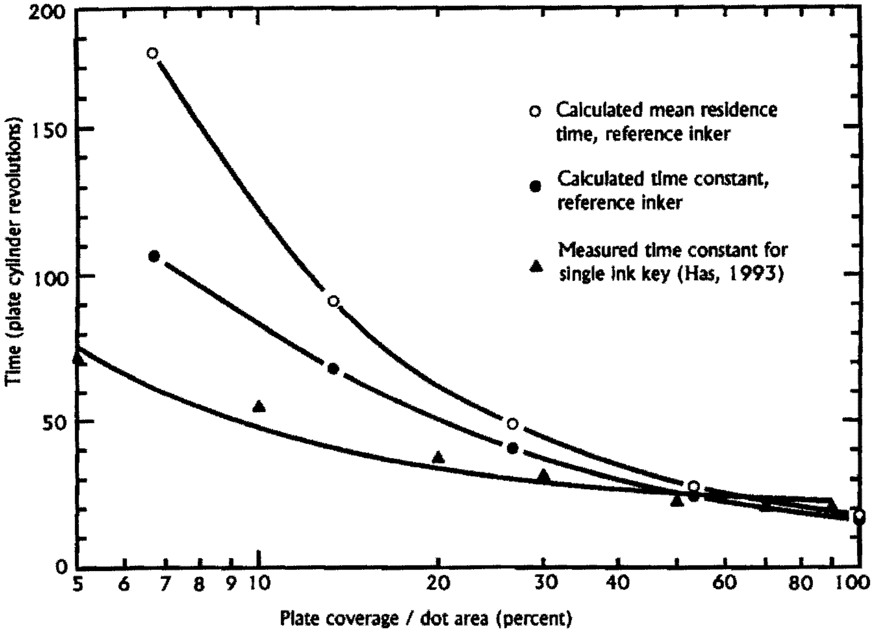


Figure 8 Calculations that show effect of ductor type feed in reducing time constant of response to step increases in ink feedrate. Based on inker in Figure 6, 90 degree ductor sweep, and ductor dwell in ink train position of three revolutions. Plot of measured time constants versus dot area for changes in a single ink key is included for reference only.

delays, however, can be accounted for by the long transport delay of about 25 impressions between the first printing unit (of the four color press used) and the delivery (Has, 1995). Thus, it is not certain that the long measured delays (for the single color press) given in Table II are real or are due to experimental error. Consequently there is a question about the ability of this model to accurately account for transport delays in the ink train .

Taking these differences into consideration, it would seem reasonable to draw the following conclusions about the work reported on here:

1. When used to calculate quasi steady state behavior, the calculation model presented gives quite good results, as demonstrated by the calculation of the worst ghost generated by the plate cylinder gap. This type of calculation has the added benefit that a given effect can be

calculated in isolation by assuming the appropriate conditions. For example, by assuming a constant ink feedrate in this calculation, the disturbances due to the ductor were eliminated. This allowed the plate gap generated disturbances to be seen in isolation. This method of course can also be used to determine the ink film thickness disturbances produced by other effects such as the ductor roller and that of adding rider rollers like those shown in Figure 6.

2. The calculation model presented also gives quite good results when used to calculate the time constants that characterize system response to step increases in ink feedrate. This type of calculation is especially useful in assessing the effect of ductor type feed systems in reducing the system time constant, especially for light coverages.

3. Mean ink residence time provides an upper limit estimate of system time constant. The smaller time constants exhibited by real systems in responding to step increases are due to the action of the ductor roller in supplying excess ink during the initial states of the transient.

4. The actual time constants that describe system response to decreases in ink feedrate are much greater than those calculated using this model. This is most likely due to an accumulation of dead or imbibed ink on the rollers that only becomes active during changes that act to reduce the volume of ink stored on the rollers.

5. The greatest impediment to accurately calculating total response time of an inker lies in the question of the ability of this method to accurately predict delay time, D, illustrated in Figure 1.

## Acknowledgments

The earlier published studies by Harry Hull and by Debbie Guerrette were very helpful in developing the calculation model described here. The author is also very grateful to Debbie Guerrette for making available her unpublished Primary Ghost Algorithm. This afforded a method for independently calculating ghost magnitude, which was used as a check.

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