# CONTROLLABILITY OF A LITHOGRAPHIC PROCESS

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ABSTRACT

The advent of automatic control in printing brought about the problem of controllability. Systematically applied to the output variables, to color and register, the controllability analysis reveals some serious limitations of press performance and explains causes of inefficiency of some devices. Finally, it has been shown how a system approach helps to overcome the controllability problem.

Comparison of lithography and rotogravure shows that the main difference between them is in controllability of color: Offset presses are, at least partially, controllable, while gravure presses are not, and this might explain why for so many years, gravure cannot live up to the expectations of its proponents.

So, what is it, this controllability, that renders whole technologies inefficient.

## 1. Subject of Controllability

The term itself was coined by R.E. Kalman [1] in 1961. After the concept of controllability (and dual to it concept of observability) was introduced, intensive development and research efforts have been ensuing for more than 20 years. Now we can discern complete and incomplete, total and partial, state and output, strong and weak controllabilities [2,3].

Apart from the general theory developed, this powerful concept also allows a simple , no-nonsense qualitative approach that will be used here:

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We say that we have complete controllability of a process if each and every variable of the output can be controlled by manipulating its inputs.

This notion of completeness will be our main tool in the analysis of controllability of a lithographic process.

1.1 Manual control: Qualitative, by compromise. Pressmen have no problem with controllability: They control "by appearance", with a single criterion to make a printed signature attractive, and if skies are greenish or sand is reddish, it does not bother anybody.

The ability to use judgement, "semantic selectivity" while controlling printing permits pressmen to compromise some insignificant parts of print while adjusting color within apparently inconceivably wide range of optical densities (ODs) - in order to compensate for some press or plate defects, or simply to exercise some "artistic" discretion.

As an example, Figure 1 presents a distribution of ODs throughout the 35"-wide web for a typical 4-color job. One can see that ODs are set in a 1:2 range - from 0.85 to

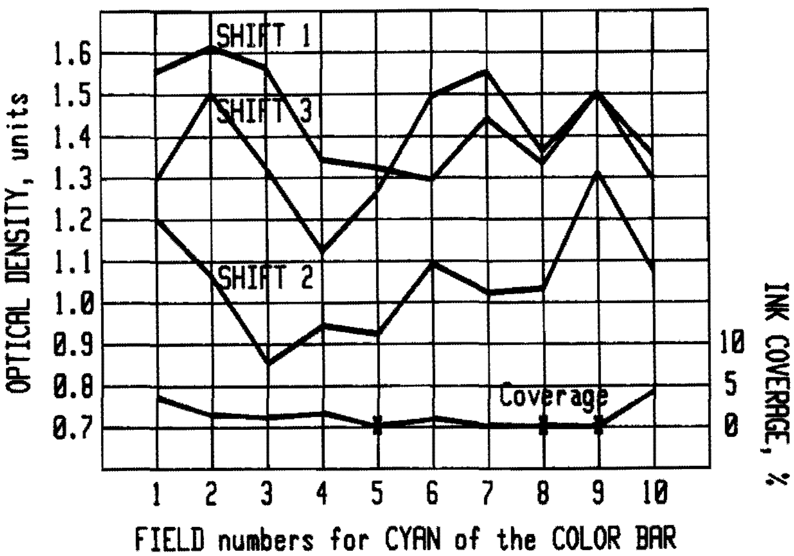



FIGURE (1) Three shifts' difference in color adjustment: Nonsensitive case (* marks non-image areas)

1.62. Moreover, every shift/crew seems to have its own "aesthetic criteria": they make changes almost within the same range. For instance, in the area of field #3 was printed a huge cigarette colored for some reason a little bluish. Shift #1 made it densely blue (OD=1.56), and the next shift made it very pale by reducing CYAN adjustment by 0.7! But the other side of the same job (Figure 2) had a couple of pictures very sensitive to MAGENTA in areas #4,5. All three shifts have kept them within a narrow margin of 0.1 - 0.15 (no matter that the set values of OD differ by 0.3 - 0.4).

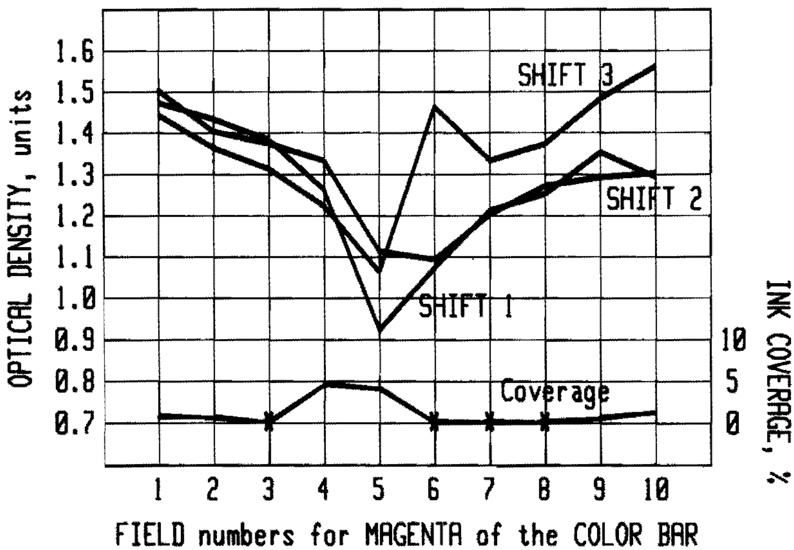



FIGURE (2) Three shifts' difference in color adjustment: Sensitive case (* marks non-image areas)

1.2 <u>Automatic control: Quantitative, by tolerances.</u> A computer not only does not see the signature (this is minor), but it cannot exercise the judgement about the significance of different parts of print - and this is critical.

Indeed, for computer control, both the sensitive case (Figure 2), and nonsensitive case (Figure 1) are of equal importance, because it takes a human to find out their difference in appearance, and the sensitivities of those appearances. Moreover, ODs in non-image areas are of the same importance to the control system, because again it takes a human to find out that the area is truly a non-image one.

Therefore, the only option left to the automatic system is to follow closely the pressman-adjusted color bar, by quantifying both the reference ("proof") bar and the actual, currently-measured bar, and by quantifying this "closeness" as well - with a system of tolerances. And here is where controllability comes into play: in order to be able to exercise such a quantitative control, we have to be able to control each and every variable of output, both color and register.

1.3 Conditions of controllability. There is conceptual difference between the two requirements, EACH and EVERY:

EACH is the necessary condition of controllability; otherwise, the variables that do not belong to the set of EACH are uncontrollable, and the system does not meet the controllability requirement.

EVERY is the sufficient condition of TOTAL, or at least COMPLETE controllability; it means that not only single output variables can be set to predetermined values, but also any arbitrary combination of those variables is achievable in finite time.

In our case of offset press control, we usually meet the necessary condition, but the controllability usually is INCOMPLETE: Almost always we fail to meet the sufficient condition, and the automatic devices developed become more or less controllable, but never totally controllable.

The conditions of controllability have less to do with controls and more with press designs. To reach higher controllability we have to redesign the press, not its control system.

This is why we begin the press controllability analysis with discussion of the inker design.

## 2. Controllability of Color

Color controllability means that the optical density of each point on the signature can be re-adjusted; and complete controllability means that the OD of every point can be re-adjusted independently of its neighbors.

Thus, the necessary condition of controllability calls for controlling color at least along one dimension, say laterally. This is incomplete because along the second dimension, i.e. circumferentially color adjustment is impossible. To make inker controllability complete, or even total, we have to have a two-dimensional control of an inker, both circumferentially and laterally.

Unfortunately, this is not the case now, at the cost of severe constraints of controllability.

2.1 Circumferential constraint: Unconditional. The offset printing, like rotogravure has no means of controlling color circumferentially on the press. Every circumferential column of print usually has several pictures with different contrast and half-tone values. Only one of those values can be adjusted, and all others have to be compromised.

Lithography as a technology is, in essence, the half-tone printing based on one parameter, the dot size. Therefore, it is only natural that the dot-related research is so comprehensive and diverse. Starting with the Davis-Murray equation, and its Yule-Nielsen refined version, all the way through the Tollenaar research [4], and to the latest fad of the System Brunner [5], the non-linear relationship between the density of color and the dot size has been examined over and over again.

But, this research, while helpful a lot in the pre-press operation, is purely academic as far as the press control is concerned: Pressmen cannot control the half-tone at every place of print on the press.

The half-tone approach is getting more and more fashionable also in rotogravure. And it is instructive to learn what a formidable difficulties they encounter while trying to make up for the press condition in the pre-press operation ([6], Gradation control, p. 586).

Thus supposedly artificial notion of incomplete color controllability on the printing press turns out to be a major limitation on adjusting the main technological parameter, the dot size, during the press operation.

2.2 Lateral constraint: Spatial frequency response. While color is not controllable at all in the circumferential direction, there exists some constraint in the lateral direction as well.

Figure 3 presents several frequency response curves of a typical inker design. The curves have been obtained experimentally from printing a specially designed test form*. The spatial frequencies adjusted with harmonic ink flow cause the harmonic response of printed ODs.

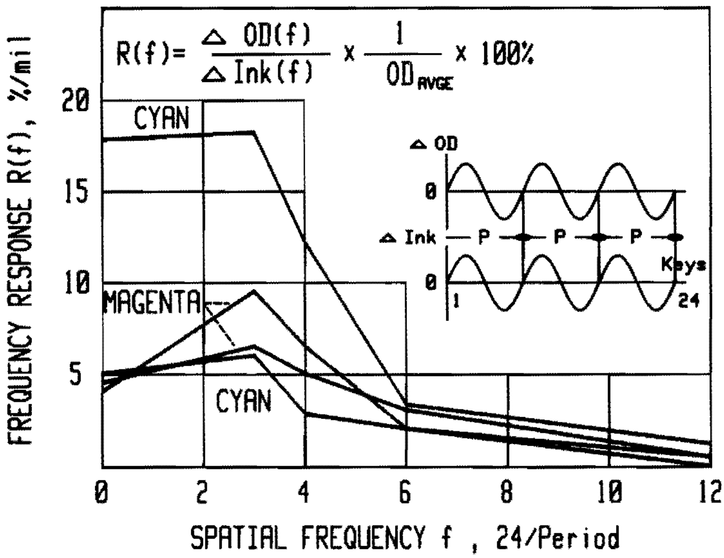



FIGURE (3) Frequency response of an inker: A typical low pass filter (Period = P keyzones)

For a 24-key inker, the highest spatial frequency is f=12 Hz**, where say all odd-numbered keys (k = 1,3,5,...)

*R.E. Harding took active part in the analysis of the test results.
**Hz (hertz) is a number of cycles per fountain.

are up, and all even-numbered keys (k = 2,4,6,...) are down, i.e. the spatial period comprises two key zones; the 4-key period corresponds to f=6 Hz; the 6-key period (3 keys up, 3 keys down) corresponds to frequency f=4 Hz, etc.

For a particular test form with well-balanced ink coverage, the output, the responding harmonics of OD can be presented as percentage change of the base, of the "zero" harmonic OD. Such an approach, while not rigorous, serves the purpose of proving the stand-point with simple means.

All frequency response curves of Figure 3, while different in value for every inker tested (due to difference in roll alignment, ink transfer values, etc.) present the typical transfer functions of low-pass filters with cut-off frequencies of 4-6 hertz. This means that in order to achieve some color change one has to control 2-3 adjacent keys together, and trying, say, to set one key up and the next to it key down will have no effect. Pressmen know it well, always adjusting smooth key profiles.

The low-pass feature of offset-press inkers is due to the vibrator rolls' effect which spread the ink laterally, across the web. The usual continuous fountain blade perfectly fits this low-pass nature of the inker, and segmenting of the blade has mostly an emotional appeal, implying that higher controllability of ink is attainable. It is not, because so long as vibrators are used, no matter how narrow is the segmented key opening, the subsequent vibrators will destroy the narrow ink flow by spreading the ink. Only elimination of vibrator rolls can widen the frequency response of inkers, i.e. make them more controllable.

By the way, this frequency-dependent transfer of ink in the offset press inkers has been the main reason why the adaptive Fourier transform pair was used as the inker's model in the Harris Densicontrol system [7].

2.3 Vibrators' influence: Unnecessary constraint. Another interesting case of vibrator rolls' smoothening effect has to do with the inker's restart.

When the press is down, its inkers are "silenced": both their inputs (ductors) and outputs (form rolls) are disconnected from the ink train. But, when the press is "down", it is in motion most of the time: inching, threading the web, sequencing, etc. result in an output of at least 200-300 "white" signatures. At this time, the inker, disconnected from its input/output but connected to the running press, "levels off" the ink distribution - both sequentially, with its feed rolls, and laterally, with its vibrator rolls. This uniformity of ink layers at all ink rolls, emerging from the idle inker's dynamics, destroys the adjusted, during the previous run, ink distribution. It takes up to 1500-2000 wasted signatures to restore the previous ink distribution during the following restart.

One of such cases is presented in Figure 4. The RUN curve shows the distribution of ODs during the previous run. Then, after "printing" 230 white signatures with disconnected inker, the restart occurred, and the RESTART curve shows the ODs scanned after the inker was ON for 70 signatures. As a result, the distribution was smoothened: The standard deviation was reduced by a half - from $\sigma = 0.31$ to $\sigma = 0.148$. And it took 370 more signatures to restore the ink distribution.

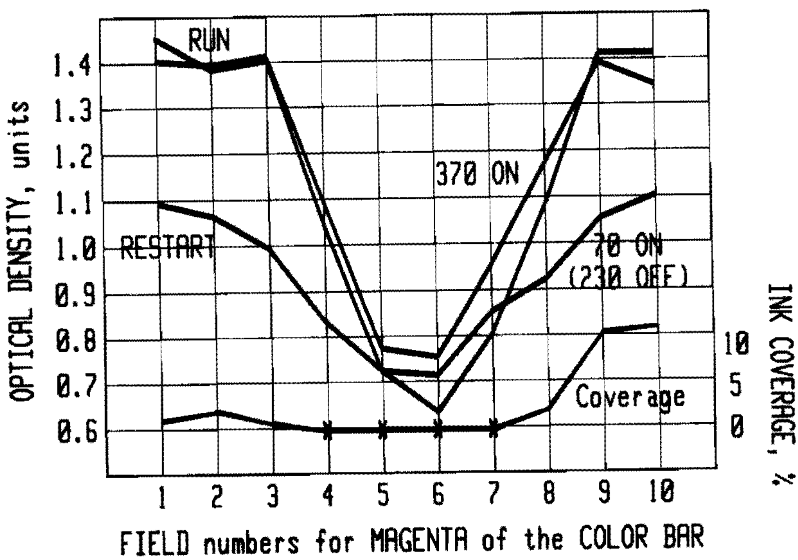



FIGURE (4) Vibrators as smoothing filters: Restart vs. Run density distribution (* marks non-image areas)

The solution to this problem seems to be evident: You have to preserve the memory of the inker by declutching it when the press is down. Indeed, this is what the Roland AG patent [8] proposes.*

It is worth noticing that the dominant effect here was of the vibrators, not of the feed rolls: The average value was reduced from m = 1.121 to m = 0.932, while the influence of feed rolls calls for its increase. This is almost always the case in our experiments, with few exceptions.

## 3. Controllability of Register

By contrast with color controllability, the controllability of register seems to be all right: We can control register both circumferentially and laterally. But in reality the situation is even worse: controllability is incomplete in both dimensions.

Indeed, as long as the web is considered a "solid body", with no local spreading or shrinking, the register controllability is complete. But paper is a very volatile medium, and depending on non-uniformity of water coverage, local shifts in register can occur in any place. Accordingly, complete controllability of register now should mean an ability to re-adjust register in every point of print independently of its neighbors.

The requirement seems to be unrealistic, but not unnecessary. The Harris Color Bar used in our experiments has register patterns both at the left-hand and at the right-hand half of the web. Comparison of their differences has proved to be rather informative.

Both this information, and the observations of pressmen's performance tend to confirm that not only color, but also register is controlled "by appearance" and by compromise: Register of a particular most significant picture is adjusted, and other pictures are compromised. This being the case, we face a set of constraints close to the ones found for color.

*Patent [8] does not mention the vibrator rolls' effect; it also does not emphasize the significance of lateral ink flow. But it does not matter, the cure (declutched ink train) remains the same.

3.1 Circumferential constraint: Variable cocking. Problems with this constraint can be better understood on a simple example presented in Table 1.

During an 11-hour period of the same run, 5 samples of saveable copies were taken and analyzed. The range of misregisters for saveable copies was up to 18.5 mils, and the very low correlation between the upper and lower side of the web suggests that the wide range found is due to re-adjustments of register, not because of some elongations of the web due to changes of its moisture. This seems to validate the hypothesis of control by compromise not only for color, but for register too.

TABLE 1: Circumferential CYAN

| SAMPLE | | UPPER | | | LOWER | | |
|---|---|---|---|---|---|---|---|
| # | TIME | WORK | GEAR | COCK | WORK | GEAR | COCK |
| 1 | 10:30a | 8.5 | 7.0 | 1.5 | 5.0 | 6.5 | -1.5 |
| 2 | 11:30a | -9.5 | -6.5 | -3.0 | 0.0 | 1.5 | -1.5 |
| 3 | 1:00p | -10 | -9.5 | -0.5 | -6.0 | -6.0 | 0.0 |
| 4 | 2:00p | 3.5 | 2.5 | 1.0 | 5.0 | 4.5 | -1.5 |
| 5 | 9:20p | -7.5 | -3.0 | -4.5 | -3.0 | 0.5 | -4.5 |
| RANGE, mil | | 18.5 | 16.5 | 6.0 | 11.0 | 12.5 | 4.5 |

TABLE 1: Circumferential MAGENTA

| SAMPLE | | UPPER | | | LOWER | | |
|---|---|---|---|---|---|---|---|
| # | TIME | WORK | GEAR | COCK | WORK | GEAR | COCK |
| 1 | 10:30a | 0.0 | 2.0 | -2.0 | 1.0 | 0.0 | 1.0 |
| 2 | 11:30a | -7.0 | -9.0 | 2.0 | 4.0 | -2.0 | 6.0 |
| 3 | 1:00p | -7.0 | -9.0 | 2.0 | 1.0 | -4.0 | 5.0 |
| 4 | 2:00p | -2.0 | 2.5 | .5 | 5.5 | 0.5 | 5.0 |
| 5 | 9:20p | -3.0 | -1.0 | -2.0 | -2.5 | -1.0 | -1.5 |
| RANGE, mil | | 7.0 | 11.0 | 4.0 | 8.0 | 4.5 | 7.5 |

On the other hand, the difference between the misregisters of the workside and the gearside of the web, so-called cocking of circumferential misregister, had a range of up to 7.5 mil, with rather significant correlation between the upper and lower sides. This observation suggests that local misregisters do exist and that they can be significant. Furthermore, the variable cocking found does not say too much about real misregister somewhere on a crucial picture printed: there misregsister may have a very small correlation with the misregister found on the color bar. This is a serious constraint on controllability.

From this viewpoint it is clear why the closed-loop register control, so successful with the dry web of rotogravure, is faltering with the wet web of offset. Indeed, the place where the register mark is printed may have little or no correlation with the picture's misregister, and instead of a control the closed loop will become a disturbance. Referring to our example in Table 1, let's assume that the register mark has been printed on Magenta's lower workside. Then, on the gearside, a misregister will randomly fluctuate in the range of 7.5 mils while a pressman will time and again reset the closed loop from the mark that is a feedback from something else.

3.2 Lateral constraint: Variable shrinking. Even more dramatic result can be obtained for the lateral misregister. Because of no tension in the lateral direction, the web is more susceptible to the non-uniformity of water coverage in this direction.

TABLE 2: Lateral CYAN

| SAMPLE | | UPPER | | | LOWER | | |
|---|---|---|---|---|---|---|---|
| # | TIME | WORK | GEAR | SHRINK | WORK | GEAR | SHRINK |
| 1 | 10:30a | -1.5 | 3.5 | -5.0 | -2.5 | -8.5 | 6.0 |
| 2 | 11:30a | 3.0 | 9.0 | -6.0 | -5.5 | -11.0 | 5.5 |
| 3 | 1:00p | 3.5 | 10.0 | -6.5 | -9.0 | -12.0 | 3.0 |
| 4 | 2:00p | -5.5 | -7.5 | 2.0 | 1.5 | 4.0 | -2.5 |
| 5 | 9:20p | -0.5 | 0.5 | 0.0 | -3.0 | -3.5 | -0.5 |
| RANGE, mil | | 9.0 | 17.5 | 8.5 | 10.5 | 16.0 | 8.5 |

TABLE 2: Lateral MAGENTA

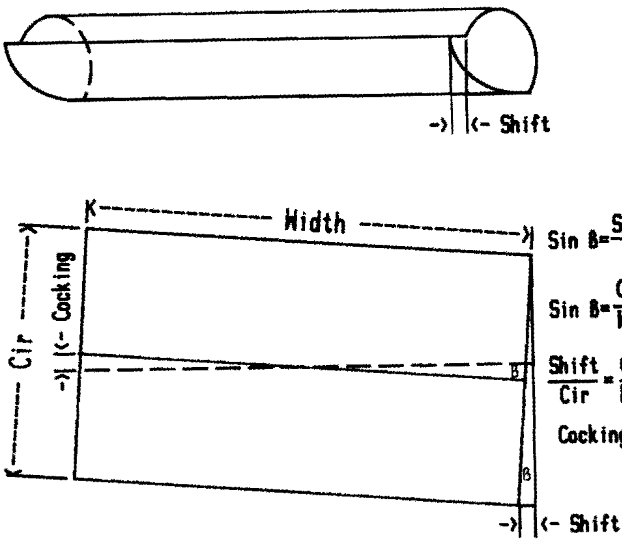
| SAMPLE | | UPPER | | | LOWER | | |
|---|---|---|---|---|---|---|---|
| # | TIME | WORK | GEAR | SHRINK | WORK | GEAR | SHRINK |
| 1 | 10:30a | -0.5 | 4.0 | -4.5 | -3.0 | -7.5 | 4.5 |
| 2 | 11:30a | 5.0 | 10.0 | -5.0 | -4.0 | -8.5 | 4.5 |
| 3 | 1:00p | 2.5 | 9.5 | -7.0 | -6.5 | -10.0 | 3.5 |
| 4 | 2:00p | -4.0 | -8.0 | 4.0 | 2.0 | 7.5 | -5.5 |
| 5 | 9:20p | -1.0 | 2.0 | -3.0 | -2.5 | -3.0 | 0.5 |
| RANGE, mil | | 9.0 | 18.0 | 11.0 | 8.5 | 17.5 | 10.0 |

Using the same 5 samples as before, Table 2 presents the results for the lateral dimension. Here the results seem to repeat the data of Table 1: The range of misregisters up to 18.0 mil; the difference between the gear- and workside of up to 11.0 mil; the same weak correlation between the upper and lower side for misregisters, and rather strong correlation for their differences.

Moreover, all conclusions about local misregisters and deficiencies of the closed-loop register control are even more valid for the lateral misregister.

What makes the result so significant is that the difference in lateral misregister, which is caused by the spreading/shrinking web and which is approximately by 50% larger than that of circumference (11.0 mil versus 7.5 mil), is completely uncontrollable: there are no means to correct this misregister*.

3.3 Skewness as constraint. Another example of "complete register uncontrollability" is presented on Figure 5: Lateral shift in putting on the plate. Such a failure to "make ends meet" causes cocking. Hence, an unconditional lateral misregister brings about almost equal circumferential misregister, as it is explained in Figure 5. No combination of input controls can correct that. The plate must be re-adjusted.




$$\text{Sin } B = \frac{\text{Shift}}{\text{Cir}}$$

$$\text{Sin } B = \frac{\text{Cocking}}{\text{Width}/2}$$

$$\frac{\text{Shift}}{\text{Cir}} = \frac{\text{Cocking}}{\text{Width}/2}$$

$$\text{Cocking} = \text{Shift} \times \frac{\text{Width}/2}{\text{Cir}}$$

Figure (5) Interdependence of register constraints: Shift vs. cocking

*Some printing houses use bussel wheels for the purpose, but this is insufficient.

3.4 Uncertainties in dynamics. It is a well-known fact that after some significant disturbance, such as a splice, restart, or blanket wash, color usually returns to its pre-disturbance state, but register, more often than not, is not restored to its value. It usually takes pressman's interference to do that.

This uncertainty also occurs, to a lesser degree, every time when register is changed. This again should be considered as a specific constraint on register controllability.

Figure 6 presents an example of such a constraint. During a normal production run, our press interface computer was programmed to introduce a full cycle of register changes: 5 sec UP - 5 sec STOP - again 5 sec UP - again 5 sec STOP - then 5 sec DOWN - etc. Correspondingly, the change of real misregister taken from the color bar has shown a substantial inertia (no STOPS - the register kept changing) with variable delays of up to 50-100 signatures (5-10 seconds).

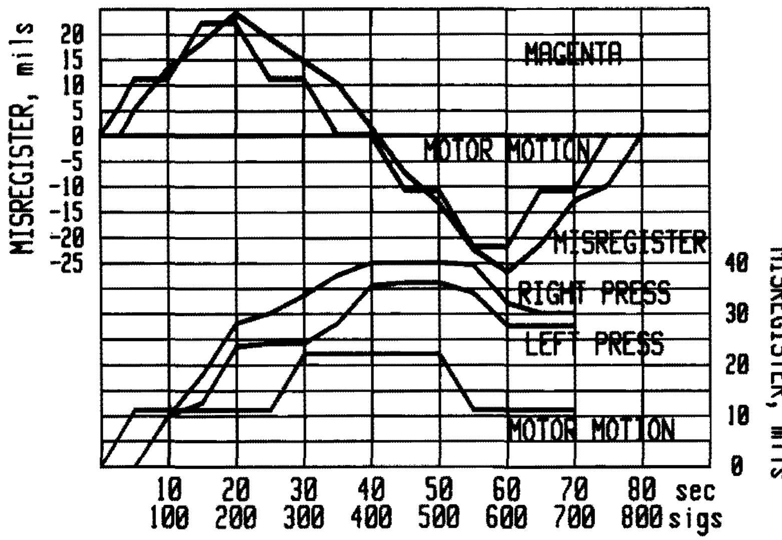



FIGURE (6) Circumferential Register dynamics:
Actual misregister vs. cylinder displacement.

But the next run on the same press (lower part of Figure 6) showed a different dynamic. The left and right webs of this 8-unit press behaved somewhat differently: overshooting became almost 100% (40-mil misregister for a 24-mil displacement), and the presses continued on with this overshooting for a long time.

Here again, for a manual control this is only a problem of big register inertia, but it is a conceptual problem for the computer control.

## 4. System Approach to Controllability

The overview of the lithographic press' controllability given above paints a bleak picture: Offset as technology perfectly fits the manual control, and it is incompatible with the computer control. And no wonder: for many years it was evolving as a manual-control technology, and in order to successfully accommodate such a revolutionary means as a computer, a lot should be changed, both in technology, and in press design.

Up to now we have avoided the major question: What do we want from the computer control of printing? What advantages should it bring? Do we need a computer on the press at all? This is a system engineering question, and the answer to it is almost trivial: We are aiming at ends commensurate with available means, and as the means are progressing, more ambitious goals will be pursued.

Thus, we should explore what can be done now, with the existent limited controllability, and then project the development into the future.

4.1 Reproduction and controllability. The first major problem has to do with the essence of printing, the reproduction: The customers, both publishers and advertisers, want to get their orders consisting of copies of what they want: all copies should be identical to the copy they have approved. The situation presented in Figure 1, where every shift sets its own standards, is unacceptable to them.

Computer control is perfect for that: By controlling the printing process within narrow tolerances, it assures the complete reproducibility throughout the whole run.

Limited controllability is not a problem in this case: Pressmen take care of it by providing the necessary compromises for the office copy, and the computer system provides control within small variations around the compromised values.

4.2 Paper waste and controllability. The second major problem is the efficiency of the printing process. Web offset presses waste at an average 15.5% of paper [9], and at a cost of $40,000 per percent annually, paper waste costs more than the rest of press operation: its labor, equipment, buildings, etc.

Computer control by reducing waste by 2-3% can return investment on it in 12-18 months. Such a waste reduction can be achieved with applying the time-optimal control during restarts, makereadies and color/register adjustments.

The time-optimal control design depends greatly on the condition of controllability ([2], pp. 346-349): the system must be completely state controllable. But, here we are talking about controllability in its usual narrow sense [1,2,3], about its dynamic characteristics, that can be satisfied with the existing inker design.

4.3 Computer numerical control: A process. As soon as the computer control of printing is implemented, and the 2 major goals, mentioned above, are achieved, a continuous improvement process will follow.

Indeed, this first step in computer control will change the base of press operation - from the qualitative to the quantitative, numerical. The numerical base, in order to become more and more efficient, will foster improvements of press design in the direction of better and fuller its controllability. This in turn will advance the computer numerical control (CNC) system itself.

## LITERATURE CITED:

[1] Kalman, R.E., "On the General Theory of Control Systems", Proc. IFAC, vol. 1, 1961, pp., 481-492.

[2] Kuo, Benjamin C., "Digital Control Systems" (SRL Publishing Co., Champaign, IL), 1977, 560 pp.

[3] Chen, Chi-Tsong, "Introduction to Linear System Theory" (Holt, Rinehart and Winston, Inc., NY), 1970, 450 pp.

[4] Tollenaar, D. and Ernst, P.A.H., "Conditions for Halftone Printing", Advances in Printing Science and Technology, vol. 3, 1964, pp. 1-15.

[5] Buston, Virgil J., "Eurostandard: The System Brunner", High Volume Printing, 1983, March/April, pp. 23-30.

[6] Troxel, Donald E., Schreiber, William F., Goldwasser, Samuel M., Khan, Malik M.A., Picard, Len, Ide, Michael A. and Turcio, Carolyn J., "Automated Engraving of Gravure Cylinders", IEEE Trans. Systems, Man, Cybern., vol. SMC-11, no. 9, September 1981, pp. 585-596.

[7] Brovman, Y.Z. and Murray, R.R., "An Adaptive Control System for Presetting a Printing Press", IEEE 1982 IECON Proceedings (Nov. 15-19, Palo Alto, CA), pp. 56-61.

[8] Wirz, Burkhardt; Decker, Peter; Gersheimer, Valentin; Dorn, Alfred; U.S. Patent 4,000,692 (January 4, 1977).

[9] Hill, Edward W., Jr., "1979 Waste and Spoilage Survey Report on the Heat-Set Web Offset Printing Industry", Web Offset Report (PIA, Inc., Arlington, VA), 1979, 64pp.