Optimisation of Printing Processes using Dynamic Analysis

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Abstract

The highly complex nature of printing with many parameters, which affect the press performance and quality of the finished product requires the use of statistical design of experiments to efficiently investigate the process. Orthogonal arrays have been successfully applied to many printing processes. These commonly address the quality characteristic as a single discrete variable. However, the reproduction of the graphic image requires many such quality characteristics, such as tone gain, colour and image distortion, to be simultaneously controlled. This paper presents a new and unique approach to the analysis of printing experiments using algorithms derived from dynamic analysis to simultaneously optimise multiple quality characteristics. The paper explains the background theory and the detailed methodology. The benefits of this approach are illustrated using data derived from an 8-parameter, 3 level investigation in screen-printing (18 run orthogonal array test equivalent to a 4374 run full-factorial experiment). This technique can be applied to any printing or coating application.

Introduction

The printer in order to produce good prints has to balance the solid density with the tone gain at different percentage coverage's. This has traditionally relied on the skill of the printer to subjectively assess the prints and decide on the optimum setting. There have been attempts to reconcile the effect of changing tone gain in specific sections of the curve (e.g. the shadow region by applying "contrast" analysis). However, changes in tone curves tend to be compared subjectively and by implication there is no definition of what is a good or bad tone gain curve or whether a curve is an improvement. The move towards more consistent products, which will be a consequence of the development of new ISO standards for the Graphic arts, will require both the tone gain and the solid density to achieve target values. It is also essential in the analysis of controlled experiments to simultaneously compare the effect of parameters on tone gain and solid density. This paper develops a quantitative analysis of tone gain and solid density based on concepts pioneered for the optimisation of "dynamic systems" in engineering design.

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Dynamic systems in manufacturing are those where it is necessary to achieve several criteria simultaneously. A typical example would be a plastic injection moulding where several different dimensions have to be optimised on a single part. This requires a dynamic comparison, in that the magnitude of the variability is a function of the dimensions being measured. The danger in printing is the tendency to compare tone gain curves directly and independently of the solid density. If there is little change in solid density, then a small change in tone gain curve may be significant. However, if there is a large change in solid density then a large change in tone gain may be insignificant and merely represent statistical noise in the process.

This paper first addresses the problem of establishing a common frame of reference for tone gain curves and solid densities. This led to the concept of a new expression Relative Tone Value (henceforth RTV). The computer simulations of tone gain and solid density variation used to assess different methods of interpreting the data are then described. The analysis used to optimise dynamic systems is then extended to printing. A new algorithm is proposed and evaluated using simulated data. This is then applied to practical data obtained from an orthogonal array experiment in screen-printing.

Relative Tone Value (RTV)

In order to directly compare tone gain curves with solid densities then it is necessary to use one frame of measurement. While all the values could be converted into density, this would bias the analysis towards the effect of the shadow areas because of the non-linear relationship between density and tone. However, the tone gain equation defined by Murray-Davies, produces a density independent curve. Therefore, the Murray-Davies equation was modify by substituting the desired or "target" reflection density of the solid, to calculate the "Relative Tone Value", RTV:

$$RTV(\%) = 100 * \frac{1 - 10^{-(D_t - D_o)}}{1 - 10^{-(D_{TS} - D_o)}}$$

where D_t is the density of the half tone, D_o is the density of the unprinted substrate, D_{TS} is the **TARGET** density of the solid

Thus, the RTV of the printed solid can deviate from 100%, dependent on the reflection density of the printed solid (Figure 1). The concept of target values is in line with the recent standards for four colour process printing which specify both a tone gain curve with production tolerances and the colour of each of the solids. If the use of ink of standard colorimetric properties is assumed, then the latter can be translated into a relative density, information that is supplied for reference in some of the standards.

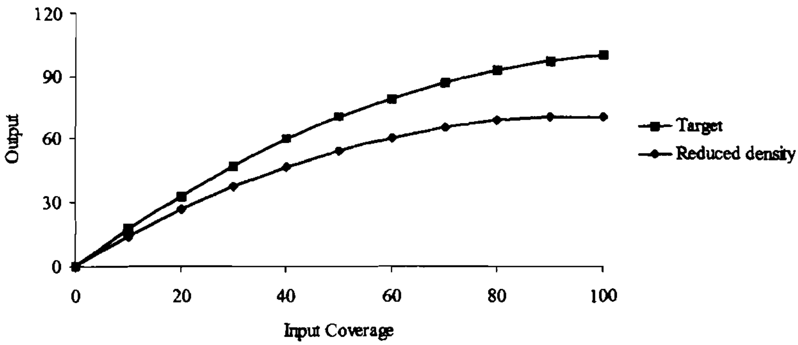


Figure 1 Effect of reducing solid density on the Relative Tone Value

Simulation of Tone Gain

The tone gain and solid density are accepted methods for assessing the quality and accuracy of the printed graphic image. Any new analysis technique must be sensitive to small changes in both these characteristics and respond in a meaningful manner. Therefore, in order to make a comparison of the performance of different algorithms under controlled conditions, a simulation was created based on the Murray Davies equation, which calculated the reflection densities of the half tone for a given tone gain curve and solid density. Both the value of the solid density and the shape of the tone gain curve could be varied independently. The reflection density of the solid was varied from 1.2 to 2.0 in steps of 0.2 with a target value of 1.6. Two generic shape of tone gain curve were used, a parabolic, which corresponds to a typical offset printing tone gain curve and an "S" shape curve, with loss in the highlight region and gain in the shadows, which is typical of screen printing.

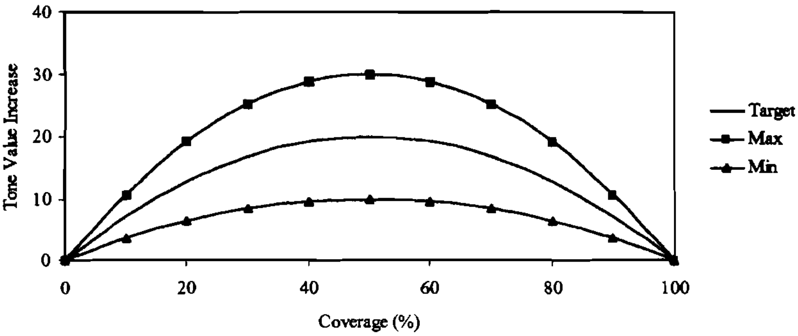


Figure 2 Range of symmetrical parabolic simulated tone gain curve

The shape of the symmetrical parabolic form of the tone gain curve was determined by the tone gain value specified for the 50% mid tone. The range of curves used to evaluate the algorithms is shown in Figure 2. This curve would allow a comparison of the relative impact of the magnitude of the tone gain with the variation in solid density for a given curve shape.

In order to investigate the effect of shape on the relationship between the tone gain curve and the solid density, this simulation was modified by including a ramp function. This increased the gain in the highlight region and thus shifted the centroid of the curve. Figure 3. The target tone gain curve for both these tone gain curves was the undistorted parabola with a 20% tone gain at the mid point. 5 linear increases in the ramp progressively shifted the peak of tone gain curve to 35% coverage.

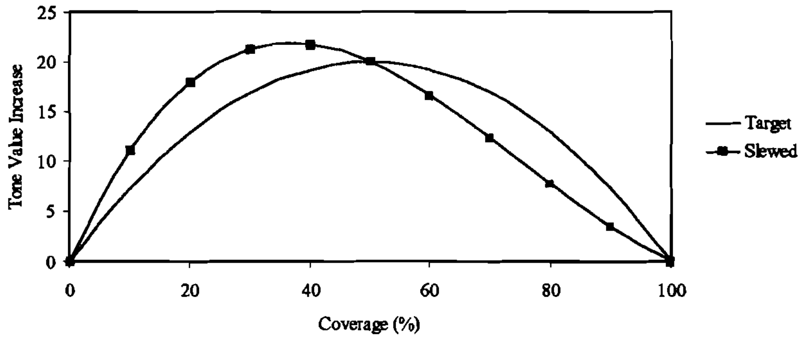


Figure 3 Parabolic simulated tone gain curve with increased gain in the highlight

The simulation of the "S" shaped Tone Gain Curve, Figure 4, allowed several parameters that defined the curve to be varied independently. The tone gain curve was based on a sinusoidal function where the magnitude of the tone gain at the quartertones could be varied independently. The magnitude of the loss in the highlight was specified at 25% coverage and the tone gain in the shadow was specified at 75 %. In addition a ramp function applied to the whole of the curve enable the point of transition from loss to gain to be moved towards the highlight region, eliminating all loss at its maximum value. The target value and the extremes of the curve used to evaluate the new analysis functions are shown in Figure 4.

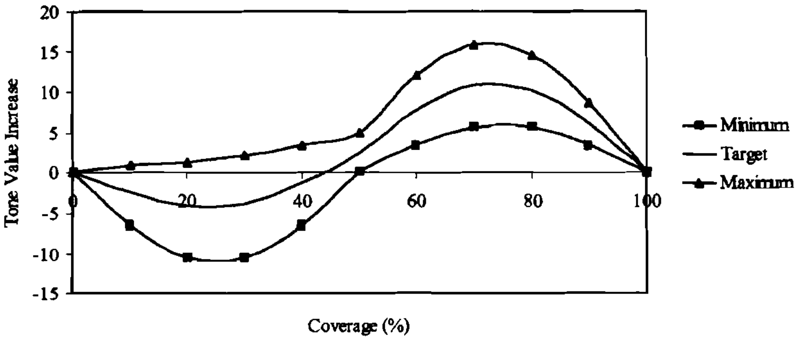


Figure 4 Simulation of "S" shaped tone gain curve

In the following section, the tone gain curves and solid densities are used to explore the sensitivity and reliability of the analysis techniques over a range of conditions.

Development of the tone gain and solid density analysis

Taguchi first proposed the use of signal to noise ratio in the optimisation of "dynamic systems" where the function of the engineering system is to produce a variable output in response to a variable input signal (Grove and Davies, 1992). This was originally conceived for systems such as braking or air bag deployment mechanisms where the performance of the system is related to variable conditions, e.g. the speed of motion, the inherent energy in the system and the desired rate of deceleration. The concepts developed for such situations have subsequently been applied in manufacturing systems, such as injection moulding, where the process has to be optimised to simultaneously achieve target values for different linear dimensions in the work piece. In half tone printing, the printed coverage should be the same as the half tones in the separation, i.e. there is a linear relationship between the separation and the printed image. If the density of the image changes then the slope of the relationship changes, increasing with increasing density. However, as well as the changing slope, there will also be a deviation due to the systematic change in the shape of the tone gain curve and the random variation of the process. While the magnitude of the noise in absolute terms may vary, if it is in proportion to the change in slope of the transfer function then it represents consistent variability. This highlights the difficulties in directly comparing tone gain curves. A large change in tone curve may be insignificant when there has been a correspondingly large change in solid density, whereas a small change in tone curve may be significant if there has been little change in the solid density.

The slope of the RTV graph can be calculated using least squares linear regression. The linear regression is constrained to pass through the origin as zero coverage will result in the substrate not being printed. Therefore, the slope of the regression line is calculated using the following form of the equation:

$$Slope, B = \frac{\sum y_i \ S_i}{\sum S_i^2}$$

where y is the value of the input signal and S is the corresponding output

The relationship between the half tone separation (the input) and the printed half tone (the output) is given by the slope, B, of the RTV. It could therefore be considered to be the "signal" that the process is transmitting. The deviation from the straight line defined by the regression analysis, represents the reliability or quality of the transfer. This is the "noise" which causes the "signal" to degrade. The deviation of the output from the slope is similar to the calculation of standard deviation for a single sample, but is obtained by calculating the residual sum of the squares based on the prediction of the output based on the slope. Thus the noise is defined as

$$Noise, Sr = \sqrt{\frac{1}{n-1}\sum (y_i - BS_i)^2}$$

The performance of the transfer process can be assessed by the relationship between the signal and the noise. The larger the signal compared with the noise the better. Taguchi combined the slope and the noise into a signal to noise ratio defined as (Taguchi, 1987)

$$Sn = 10\log_{10}\left(\frac{D}{Sr}\right)^2$$

The aim of the analysis is to produce a peak that corresponds to the desired printed image. The process can be optimised by maximising the Signal to noise ratio, Sn. In order to evaluate this function a full factorial experiment was performed with the symmetrical parabolic tone curve simulation by varying the density and the half tone curve. The signal to noise ratio falls as the tone gain in the mid tone increases (Figure 5). This is as expected as increasing mid tone gain would lead to the curve increasingly deviating from a straight line. This could be used if the target was a zero tone gain curve. However, most processes have inherent tone gain variation with coverage. Therefore, a function is required which produces a peak when the target tone gain curve is achieved. Also, there is no change in the magnitude of the curves with density. Thus, this cannot be used in this form to compare the effect of changing tone gain and density.

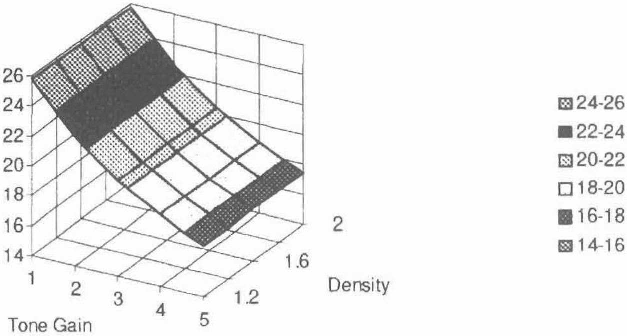


Figure 5 Variation of signal to noise ratio based on linear regression

The slope of the line of linear regression increases with both density and tone gain, as it is a measure both of the changing solid density and the deviation of the tone gain curve from a straight line (Figure 6). This would be expected based on the constraint that the linear regression has to pass through the origin, which is applied in calculating the linear regression. This expression, which is an interpretation of the average density across the whole of the tone range, would be difficult to relate to graphic images.

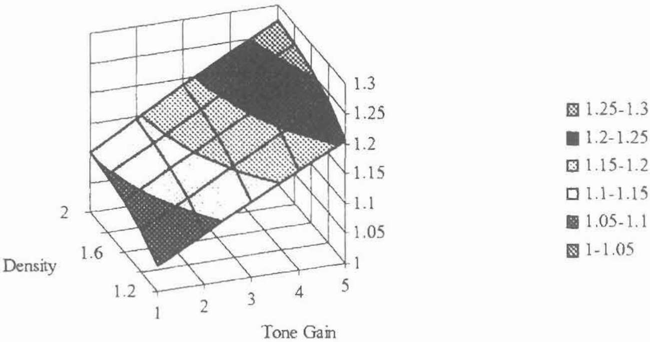


Figure 6 Variation of the slope of the line of linear regression

While the results of directly applying the regression concepts from "dynamic systems" to the RTV may be appropriate for a linear relationship with random variability, it is difficult to relate these to the graphic images. These images tend to be sensitive to subtle changes in shape of the tone gain curve and have a strong dependence on the density of the solid. The move towards standardisation, as exemplified by the latest standards from ISO, highlights the need for processes to achieve solid density and tone gain targets. Therefore, it is appropriate to develop a new form of analysis based on the concept of deviation from target values.

If there were no tone gain during printing then the relationship between the desired and achieved coverage would be a straight line passing through the 100% coverage. Therefore, instead of using a linear regression to calculate the gradient of the slope, B, the Solid Transfer Effectiveness (STE) is defined as the RTV at the 100% solid coverage. Hence, it can be interpreted in terms of the target value for solid density of the desired image.

$$STE = RTV(100\%) = 100 * \frac{1-10^{-(D_s-D_o)}}{1-10^{-(D_{TS}-D_o)}}$$

where D_s is the density of the solid.

The error between the target desired tone gain and the actual tone gain could be calculated based on the Murray-Davies equation. However, as the Murray-Davies formulae describes the tone gain with respect to the reflectance density of the 100% coverage, makes the curves independent of the solid density. The net effect is calculated by integrating the difference between target and actual tone gain curve. This gives a peak at the target value, which is independent of the solid density. Thus, again a comparison of the trade off between tone gain and solid density can not be made.

In order for a comparison to be drawn between the effect of changing tone gain curve and changes in solid density, then an estimation of the deviation was based on the error relative to a target value. The Deviation Tendency, Sr_T, is the sum of the difference between the actual and the target RTV curve (Figure 7). Note this will include a proportion of the effect of the error in the solid density, as the two curves are not coincident at the 100% coverage.

$$Deviation \quad Tendency, \quad Sr_T = \sqrt{\frac{1}{n-1}\sum (Se_t)^2}$$

The magnitude of the Deviation Tendency, Sr_T, can be compared with the Solid Transfer Effectiveness, STE, in a similar manner to the signal to noise ratio to give an Optimisation Function, Sn_T. In order to optimise the printing process, then Sn_T has to be maximised. The Optimisation function, Sn_T, is given by

$$Sn_T = 10\log_{10}\left(\frac{B_T}{Sr_T}\right)^2$$

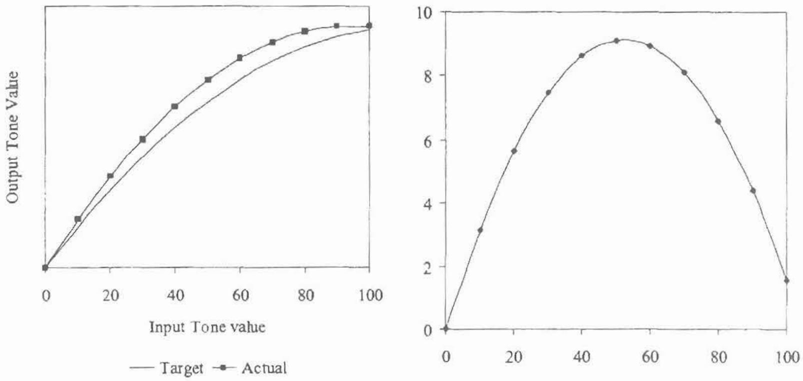


Figure 7 Relative Tone Values (left) and Sr_t (right) versus coverage

The full factorial experiment was repeated with the symmetrical parabolic tone curve simulation to evaluate this new algorithm. The Optimisation Function, Sn_T, peaks at the target value and decays rapidly as either the density or the tone gain deviate from the target values (Figure 8). Thus, in order to optimise the process to achieve the target values, then the Sn_T has to be maximised. Sn_T also responds to the interaction between tone gain and solid density. For each value of solid density, Sn_T peaks at a different value of maximum tone gain. At below the target solid density, this peak is higher than the target value and reflects the influence of increased tone gain in the half tones compensating for a lower value of solid density. Similarly, for values of the target density which are greater than the target value, then the peak with respect to the maximum half tone is less than the target value. Thus, a major advantage of using Sn_T is that the relative merits of two conditions where the tone gain curve has been manipulated to allow for changes in solid density and vice versa can be directly compared.

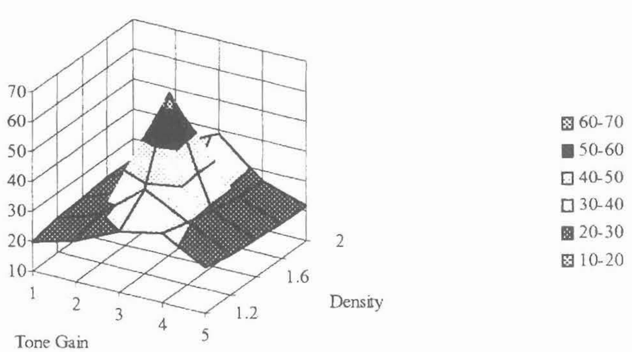


Figure 8 Variation of Sn_T against Tone gain and Solid Density for a parabolic tone gain curve

The response of the Sn_T to changing shape of the tone gain curve was evaluated by a full factorial experiment for the parabolic function with the distribution slewed by progressively increasing the ramp function. This was performed for constant solid reflection density. The target value was the same as for the previous case, i.e. the symmetrical parabolic curve. The peak value of Sn_T occurs at the target value. This decays as either the tone gain is varied or the ramp function is increased to slew the distribution (Figure 9). These give bands of Sn_T at which the error in the tone gain curves are comparable.

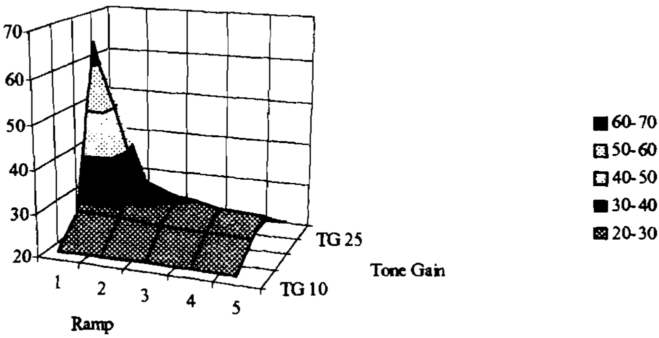


Figure 9 Effect of increasing tone gain in the highlight region on Sn_T

In view of the number of variables and the interactions, the effect of varying parameters away from the target value in the "S" shaped tone curve simulation were evaluated independently. While each parameter was varied, the other parameters, which controlled the simulation, were held constant. The peak of the Sn_T occurs at the target value as expected (Figure 10). The variation of solid density has a greater influence on the Sn_T below the target value than above. The increase in tone loss in the highlight has the converse effect. All the other parameters have an equal effect on either side of the target value.

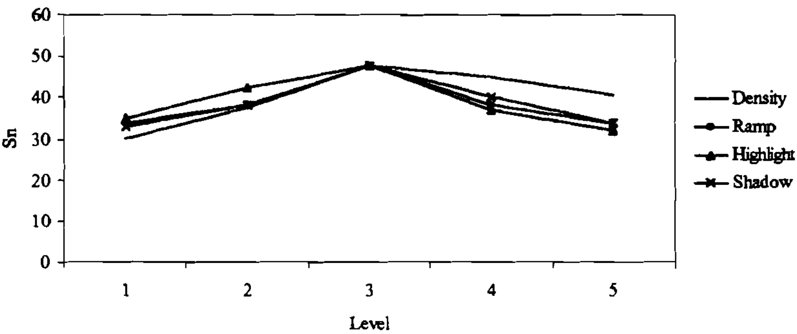
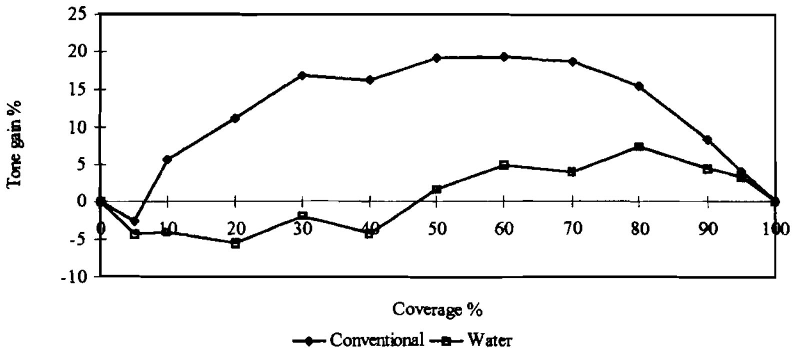


Figure 10 Response of Sn_T to changing parameters of the "S" shaped tone gain curve

Application of the Sn_T analysis

The Sn_T analysis based on the concept of the RTV, has been shown with the simulated tone gain and solid density data to be capable of comparing different tone gain curves at different solid densities. Its capability in practise was evaluated using the results from an experimental investigation into screen printing on a flat bed press. Eight parameters were simultaneously evaluated using an L_{18} orthogonal array experiment. The orthogonal array is a design of experiment where each parameter is systematically varied for each of the tests in such away that the effect can be analysed for independently. The attraction of using an orthogonal array experiment is that these parameters could be evaluated independently in 18 experimental tests, compared to a full factorial experiment, which would have required 4374 experimental tests. For further details on the use of orthogonal array techniques please refer to Phadke 1987 or Grove and Davies 1992. The parameters varied were the mechanical press variables of squeegee pressure and speed, flow coat clearance and speed, frame snap off, peel off and dwell time. Each of these was considered at three different settings. A further factor considered was the ink type. Two different ink types, a water based and a conventional UV ink were included in the array. The test image printed comprised a number of half tone scales, solids and fine line targets. These had been measured and analysed to assess the influence of the parameters on the tone gain curve and the solid density. The results from one of the half tone scales were used to evaluate the Sn_T analysis.

When the tone gain curves had been compared previously, (Figure 11), the ink type had been found to have a significant effect. Changing ink type from water based to conventional UV ink caused an increase in tone gain through out the whole of the tonal range. This transformed the "S" shaped curve into a parabolic curve. The peel off angle had little effect on the response of the tone gain curves. It produced a small reduction in the mid tone range from 40 to 80% coverage for the first increase (level 1 to level 2), but had no effect on the tone gain curve with subsequently increases in angle.



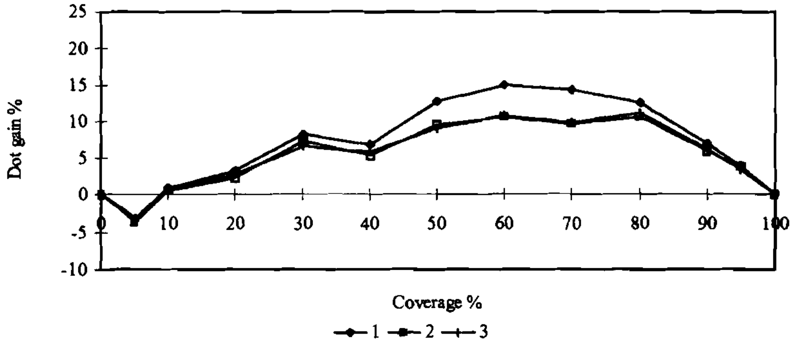


Figure 11 Tone gain curves for conventional and water based UV ink and peel off angle

The influence of the process parameters on the solid density can be seen from the graph of their effect on Solid Transfer Effectiveness, STE (Figure 12). Each of the columns in the bar chart represents the difference in the response of STE when the parameters were changed. The change from water based to conventional UV ink produces a large increase in the solid density. The effect of increasing squeegee pressure, flow coat clearance, squeegee speed and dwell time is to increase the solid density. The snap off and flow speed produce a peak of solid density at the middle setting while the peel angle produces a minimum. The magnitude of the effect of changing the ink time is 5 times greater than the next most significant effect, which is the squeegee speed. The dwell time and the flow coat speed produce the next largest effect. All the other changes produce an order of magnitude less change than the change in ink type.

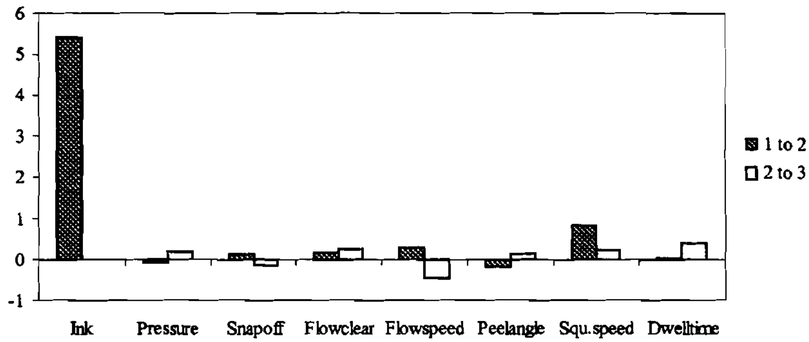


Figure 12 Effect of changing parameters on STE

The effect of changing levels on Sn_T is shown in Figure 13. The ink type has the smallest effect on Sn_T. This suggests the large change in tone curve seen previously (Figure 11) is a consequence of the substantial change in solid density. The thicker ink deposit would reduce the influence of the substrate, the half tone density being more a function of the ink colour. The peel off angle has little effect on the STE, i.e. the solid density, which makes the small change in tone gain curve of greater significance. Other parameters such as the snap off, flow coat speed and dwell time, which previously had been thought to be insignificant, because of their effect on both tone gain and solid density, have an impact on Sn_T . Flow coat clearance is shown to be insignificant on both solid density and tone gain, while the squeegee speed has an effect on the solid density and an inverse interaction with the tone gain.

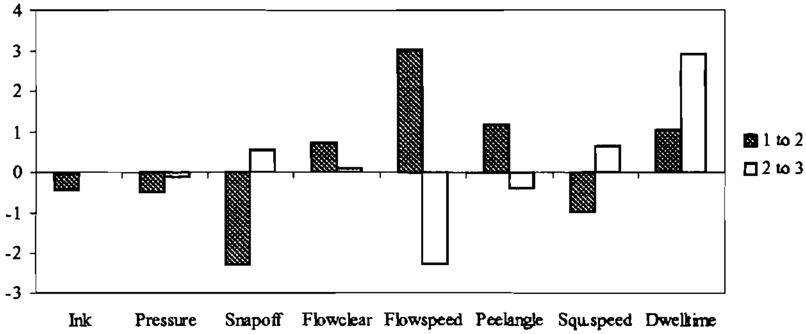


Figure 13 Effect of changing parameters on Sn_T

Conclusions

A new analytical approach has been developed for printed half tones and solids. An adaptation of the Murray Davies equation, the Relative Tone Value has been used to enable the half tone and solid densities to be accommodated in one frame of reference. An Optimisation Function, Sn_T, appropriate for half tone printing together with a Solid Transfer Effectiveness, STE and measure of Deviation Tendency, Sr_T, have been developed from concepts of signal to noise ratio originally proposed for the optimisation of dynamic systems in engineering. The maximisation of the Sn_T function will enable processes to simultaneously achieve target values for both the solid densities and half tones. It is also a powerful tool in the analysis of experiments, which may explain some of the discrepancies between experimental studies and experience. The analysis highlighted need to account for the inter relationships between tone value and solid density.

The use of the RTV and Sn_T has allowed the direct comparison of tone gain curves with solid density. This has revealed the importance of considering both facets of the process simultaneously. The interaction may explain some of the discrepancies between the view of "experience" and the results of scientific investigation, as parameters which exhibit only a small influence on tone gain and solid density, may in combination produce a significant effect. These two new algorithms may also enable rationalisation of apparently conflicting results in experimental studies.

The effects of tone gain curve, both its shape and magnitude, combined with the changes in solid density have been evaluated. The Sn_T is sensitive to both, producing a peak value when a target condition is reached. Thus, the process can be optimised by maximising Sn_T, which will also account for process variability.

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