Distortion of the image by the screen printing process.

T.C Claypole, D.T Gethin, E.H Jewell•
& W. Appleton⊗

Abstract.

A systematic investigation of the influence of screen printing process parameters has been undertaken. The investigation examined the image distortion by both analytical and experimental means. A cylinder press was fully instrumented with a customised squeegee system which allowed the tip forces, angle and hardness to be varied independently. An orthogonal array was designed which allowed 8 parameters to be fully investigated using only 18 experiments. The test sheet was composed to allow the measurement of distortion by reference to crosshairs and graduated scales on the sheet. The distortion was measured across the whole sheet using an engineering measuring machine. The investigation found that the experimental measurements tie up well with the analytical models, although there is considerable interaction between the distortion in the two orthogonal directions which deviates the behaviour from the 2 dimensional analytical models. The image distortion was found to be governed by the screen - squeegee friction characteristics, which is controlled by a number of press parameters. A finite element model of the screen distortion has been developed as a result of the investigation.

• The Welsh Centre for Printing and coating, Department of Mechanical Engineering, University of Wales Swansea, Wales.
⊗ Media studies centre, GLOSCAT (Gloucester College of Art and Technology), Gloucester, England.

1. Introduction.

Image distortion (i.e a dimensional difference in the print when compared to the film positive) is a natural characteristic of the screen printing process which becomes important when close registration is required especially with large format graphic printing. The image distortion is produced as a result of a number of process characteristics. The screen must be displaced downwards by a fixed distance to touch the substrate by the vertical action of the squeegee and the drawing action of the squeegee across the mesh may also produce a drag force on the squeegee which further produces a distortion and displacement of the image.

The aim of this investigation was to assess the effect of process parameters on the image distortion such that priorities in their control could assigned, and to develop empirical and theoretical correlations such that all press conditions may be included at prepress. The relative importance of the press parameters were studied using orthogonal array theory based on an L18 experiment. Orthogonal arrays are a subset of the full factorial and allow an investigation into the effect of many parameters in a reduced number of experiments. In this case a complete investigation into the effect of 8 parameters was carried in only 18 experiments. The press parameters investigated in the study were mesh tension, print speed, mesh ruling, squeegee angle, squeegee hardness and pressure in a combined factor, ink base and ink type.

A theoretical analysis of the distortion of the image through the printing stroke is presented in order to develop a idealised model to which the experimental results can be compared. Prior to a full orthogonal array analysis of the results the results are presented for each of the experiments so that general conclusions can be drawn and compared to the theory. Finally the relative importance of the parameters chosen are analysed prior to a formulation of recommendations and conclusions.

2. The formulation of simple theoretical models.

A simplified theoretical approach to the distortion of the printed image was carried out to provide an insight into the possible reasons for the image distortion. The theoretical approach will focus on the image distortion created by the printing process only. Distortion created by substrate ink absorption and substrate environment stability will not be addressed. The theoretical model will be address the distortion by examining 2 dimensional models of the distortion in two perpendicular directions, the distortion across the print (henceforth transverse distortion) and the distortion in the print direction. Although there may be some interaction between these models, the use of separate simplified theoretical models facilitates ease of investigation. A full description of the models may be found in ref [1].

The transverse distortion of the mesh may be simplified to a system where a single thread of mesh passes under a squeegee of length b which displaces the mesh a fixed distance downwards, the off contact gap. The displacement of the mesh causes an extension in the thread and it is the extension distribution through the thread that dictates the distortion of the image. The initial length of the thread is b + 2d, the final length is b + 2d / cos q, *Figure*

1. The thread therefore undergoes a total extension of 2d (sec q - 1) where q is the angle between the substrate / squeegee interface and the frame and d is the distance between the squeegee and mesh.

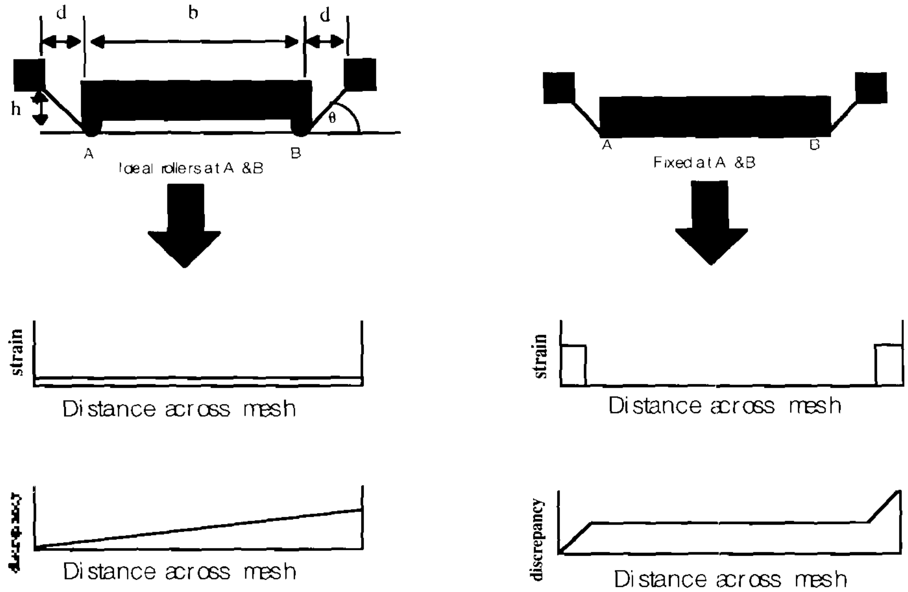


Figure 1 The two limiting cases of transverse distortion.

There are two limiting cases for the distribution of the extension. One is zero friction at the ends of the squeegee so that the extension is equally distributed through the thread, henceforth case I. The thread may also be fixed at the ends of the squeegee so that there all the extension takes place in the thread leading from the bottom of the squeegee to the frame, i.e infinite friction at the squeegee ends, henceforth case II, *Figure 1*. For case I the strain is equally distributed through the thread and may be given by:

$$\varepsilon_x = \frac{2d(\sec\theta - 1)}{(b+2d)} \qquad (1)$$

While the strain distribution under case II is given by:

$$\begin{aligned} \varepsilon_x &= \sec\theta - 1, && 0 < x < d \\ \varepsilon_x &= 0, && d < x < b+d \\ \varepsilon_x &= \sec\theta - 1, && b+d < x < b+2d \end{aligned} \qquad (2)$$

The stress in the thread is given by the product of the strain and the elastic modulus. The increased stress loading under the fixed thread condition is therefore higher and independent of the original length of the thread. The distortion of the image may be given by the integral of the extension distribution, *Figure 1*. In order to limit image distortion the ideal scenario is case II but this leads to high mesh stresses in the side parts of the mesh and high stress concentrations at the squeegee ends as a result of the high friction at the squeegee corner - mesh interface. Operating under press conditions closer to case I leads to a linear increase in the distortion across the print but is more amenable to low squeegee and stencil wear. Other three dimensional effects may vary the transverse distributions a little but the model is thought to well represent the physical process. In practice the distribution of extension of the thread lies somewhere between these two extremes.

Distortion of the image in the printing direction occurs as a result of three processes, the physical downward displacement of the screen, the finite thickness of the paper and the frictional force between the squeegee and the screen. The distortion due to the displacement of the screen may be modelled using a system where the a single thread passes under a frictionless squeegee which is held securely at both ends, *Figure 2*.

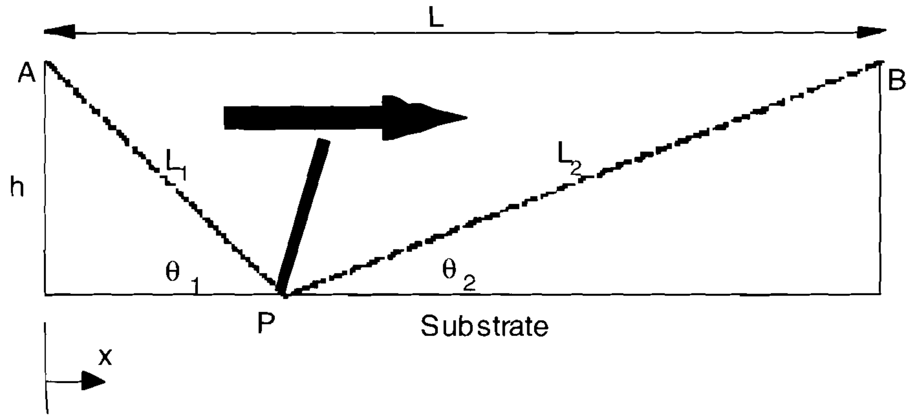


Figure 2 Print direction distortion as a result of screen displacement.

In order to print the squeegee must remain in contact with the substrate at all times. The length, and hence extension, of the thread must therefore vary with the position of the squeegee, which results in a variation of image distortion along the print. The extension and strain of the image are given by:

$$ext = \sqrt{x^2 + h^2} - x \quad , \quad \varepsilon_x = \frac{\sqrt{x^2 + h^2} - x}{x} \quad (3)$$

The image stretch is therefore high at the start of the squeegee passage and approaches zero as x >> h. When there is friction between the squeegee and the screen the tension in the mesh to the left and right of the squeegee will be different as a result of the drag force on the mesh. This drag force may be comprised of hydrodynamic and dry rubbing friction, both of which may vary with a number of parameters including the inkcharacteristics /

quantity and screen - squeegee properties. The effect of the paper thickness on the distortion of the image is peculiar to cylinder presses and occurs as the paper thickness adds a small amount to the radius of the cylinder.

Distortion of the image in the print direction due the finite paper width is a feature of cylinder screen printing presses. The reciprocating nature of the frame is controlled such that the frame travel from its zero position is in direct proportion to the angular position of the cylinder from top dead centre, i.e in phase with each other. A position on the cylinder surface may then be directly related to a position on the screen. When paper is placed on the outside of the cylinder the reciprocating frame and the rotating cylinder remain in phase but the addition of the paper changes the radius and hence the distance travelled leading to a growth in the image. Consider *figure 3*, the distance S_1 is equal to the distance x and is given by R . The addition of the paper to the outside of the cylinder increases this distance to, S_2, to (R+t) , a growth in the image on the outside of the paper.

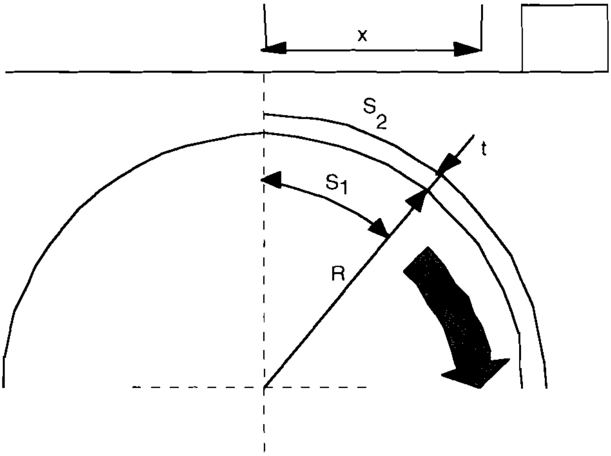


Figure 3 Image distortion as a result of finite paper thickness

For both transverse and print direction distortion, lowering the off contact gap limits the distortion caused by the downward displacement of the screen but requires higher screen tensions in order to overcome the viscous forces between the screen, ink and substrate which causes the substrate to stick to the screen. Higher mesh tensions are not however without their problems, eg higher frame weights, increased fragility and increased stretching costs. During the investigation the off contact gap was kept constant at 3 mm and does therefore not have an effect on the inferences from the experiments carried out.

3. Experimental method and practice

The experimental design is based round an L18 orthogonal array which allows the investigation of eight parameters in 18 experiments, *Table 1*. The orthogonal array method gives an economical method of investigating many design or process variables in a reduced number of experiments using a sub set of the full factorial derived through combitorial mathematics. According to standard tables factors deemed to be important in a process are placed in columns and assigned either 2 or 3 levels. The choice of number of levels is made according to theoretical estimations and experimental time available. Where factors are expected to behave in a linear, or almost linear, manner then two levels are sufficient. If however, a non linear response is expected factors must be assigned a minimum of 3 levels. Due to the balanced nature of the tables the effect of setting a parameter to a certain level may be found by averaging the results from the experiment when that parameter is set at that level as if the rest of the parameters were held constant, *ref* [2,3] . Using the orthogonal array approach the number of experiments was reduced from 2916 (2^2 x 3^6) to 18.

The parameters shown in *Table 1* were chosen as a result of discussions with industry and those which could be investigated within the scope of the experiment. They may be broadly split into 3 groups; squeegee parameters, mesh parameters and ink parameters. The L18 was designed so as to minimise the number of time consuming changes that must be carried out during the experimental programme, *table 1*, and deals with process variables over which the printer has control, such as initial frame tension, choice of squeegee, ink, mesh and the press speed. In order to eliminate the effect of paper type, and hence thickness, from the experiment a full factorial of paper type were printed with the measurements being taken on the matt paper. The experiment was successfully used to investigate the effect of the parameters in halftone reproduction and fine line printing, *ref* [4].

The most time consuming and costly aspect of the varying the parameters chosen, is the stretching of the mesh and the exposure of the image on the stencil. In order to limit this expense to 6 meshes, the mesh tension was inserted in column 1 at two levels of 17 and 21 N cm^{-1} with three levels of mesh ruling of 90 T, 120 T and 150 T threads per cm (where the T represents a thin mesh diameter), with the appropriate stencils of 15, 20 and 25 micron width respectively. This combination of mesh and stencils was chosen by experience gained through research by the SPA (UK) colour standards panel *ref* [5].

The contact angle and static pressure between the squeegee, which is made of a urethane compound, and the mesh are important parameters which influence the thickness of ink under the squeegee. The traditional parameters used by to control the squeegee action during the print process are squeegee angle, pressure and hardness. However, considerable interaction between these parameters is experienced, *ref* [6] *Figure 4*.

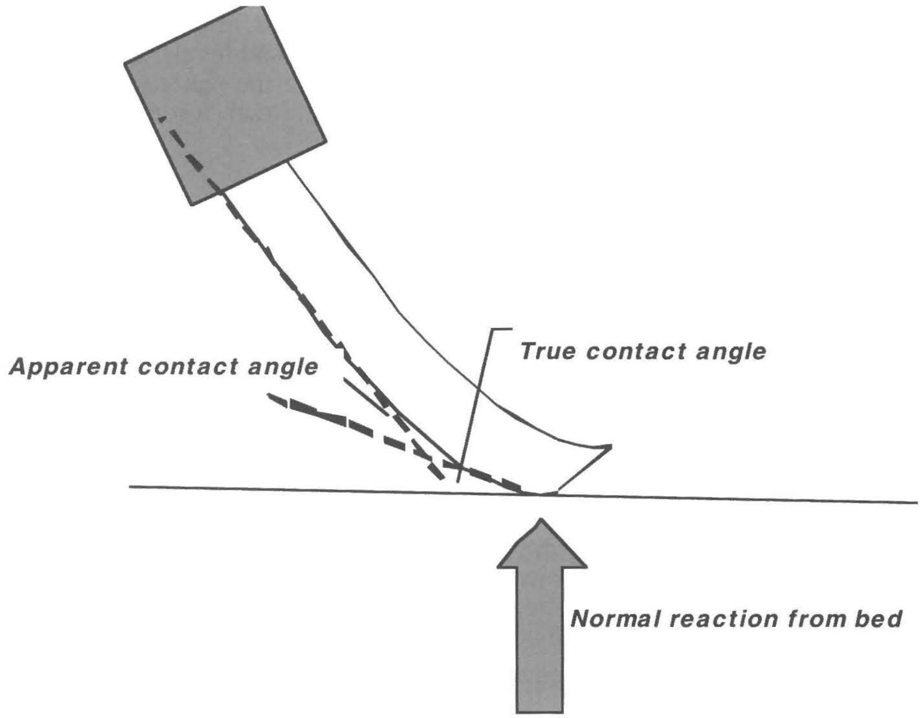


Figure 4 The interaction between apparent contact angle and the true contact angle.

All three affect the contact angle, area and pressure at the squeegee edge / mesh interface where the printing process takes place. The closer the squeegee angle to the vertical the smaller the deflection of the base of the squeegee due to the downward pressure force. Similarly a higher squeegee hardness or lower squeegee downward pressure also limit the deflection of the base of the squeegee. The deflection of the squeegee will directly control the mesh - squeegee interface angle and area.

To eliminate the interactions between the squeegee parameters of angle, downward force and hardness, the squeegee was supplemented by a stiff steel back so that its deflection would be insignificant allowing the mesh - squeegee interface angle to be measured directly as the squeegee angle. Initial trials found that the squeegee down force and squeegee edge hardness interacted so strongly that some combinations could not print at all. Subsequently, a new parameter was used which maintained the squeegee down force to hardness ratio at a constant value.

Conventionally, the setting of the squeegee load by the printer is often done by "feel", although pneumatic squeegee systems are becoming more prevalent. Threaded screws on the squeegee are tightened until a satisfactory print is obtained. To enable a pressure to be set as a control level in the array, the squeegee arm was mounted on linear bearings beneath load cells. The imbalance voltage of the load cell gives a direct ensure of the load applied at the squeegee tip. Load cells were used in favour of pneumatic system as they not only allow the squeegee load to be set more accurately but also allow the transient measurement of the load during the print stroke. The 3 load levels were defined as the static, dry load in the centre of the mesh. Since the squeegee has been designed to remove the interactions between the down force - hardness parameter, they may be placed anywhere in the array.

The ink rheological characteristics can have a substantial effect on the distortion of image and image quality. Currently the majority of the ink used is solvent based but impending legislation will force printers to turn to water based inks. To establish their effect on image distortion a traditional solvent based, water based air dried and water based UV cured inks were inserted in column 7. Column 8 also contains an ink characteristic, in line (optimised for printing solids and fine lines) or chromatic (optimised for halftone printing). For the ink colour used, black, the rheological characteristics of the inks are near identical. Inclusion of this parameter as two levels in column 8 allowed the validity of the experimental design to be assessed as their formulation, and hence rheology, should be comparable.

The other conditions used during the investigation were kept constant (*Table 2)*. The experiments were carried out over two weeks on a Sakurai cylinder screen printing press at Gloucester College of Art and Technology (Gloscat). To minimise the effect of image distortion due to substrate ink and moisture absorption the image was printed on to a 200 g m^{-2} satin paper.

In order to measure the distortion of a screen printed image a custom image was designed which facilitated the measurement of distortion through cross hairs set at 20 mm centres in 3 rows and 7 columns across a page of dimension 720 mm by 510 mm, *Figure 5*. Between the cross hair columns and rows there are a series of tonal gradation scales and geometric patterns which were used for the identification of the effect of the chosen parameters on tonal reproduction and printable line thicknesses respectively. The location of the cross hairs was measured using a SIP travelling microscope which, using a cross hair eyepiece allowed the accurate measurement of the cross hair centre. For ease of reference the rows and columns are labelled Q - S and A - G respectively

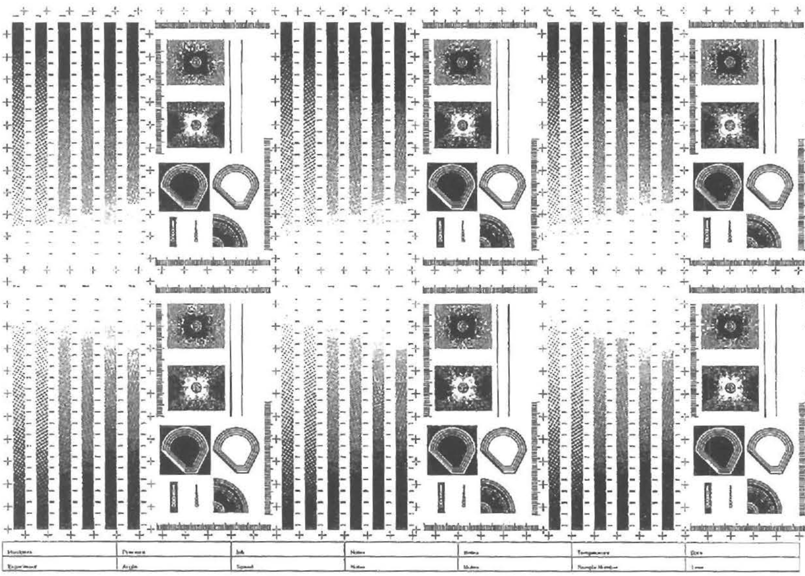
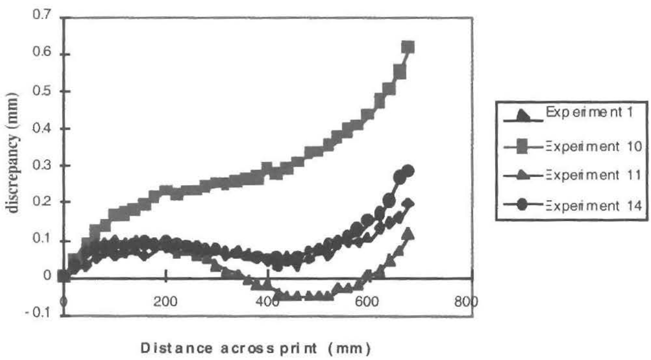


Figure 5 Test from used for the investigation.

4. Results.

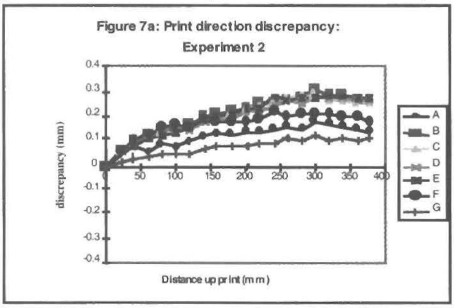
The results of the investigation are presented in two parts; firstly the a selection from the raw data is presented so that attention may be brought on the important features of the data prior to an analysis of the results using the orthogonal array. A selection of the transverse direction distortion

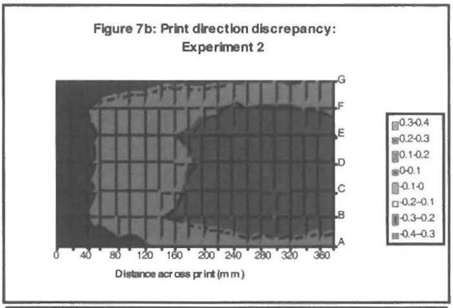
Figure 6 : Transverse discrepancy for centre row of crosshairs from selcted experiments.

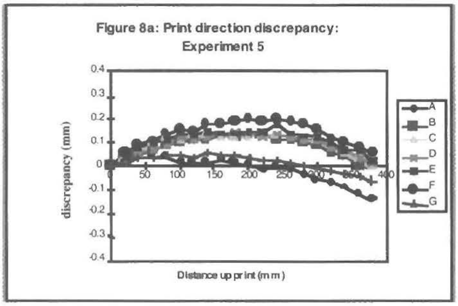


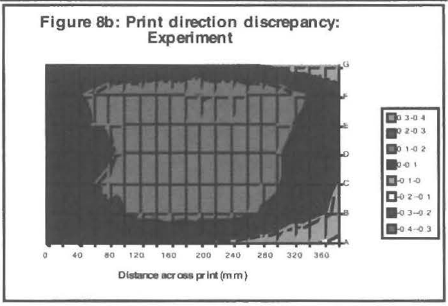
measurements for the centre row of crosshairs are shown in *Figures 6 (experiments 1, 10, 11, 14)*. The discrepancy is defined as the paper cross hair location - film cross hair location. *Figure 6* shows that the theoretical transverse distortion model (*Figure 1*) is in reasonable agreement with actual distortion of the image. Generally the gradient of the discrepancy curve (i.e the strain) is steepest at the edge of the print and shallow across the centre of the print. Occasionally the discrepancy across the centre of the print became negative, i.e the image had contracted. The implications of this phenomena will be addressed in the discussion.

Typical print direction distortion curves are shown in *Figure 7 and 8 (experiments 2 and 5 respectively)* where the left (a) figure represents a standard x - y plot of distortion for each of the crosshair columns while right hand figure (b) is a "plan view" of the distortion across the page. Generally, while there is image expansion in the print centre (columns B - F) , the edges of the print show print contraction (columns A and G).









A summary of the results obtained from the orthogonal array analysis of the results is shown in *Table 3*. The results relate to row R and column C of crosshairs and are representative of the results from all the row and columns. A factor is deemed to have an important effect when the distance between curves at each level is large. A linear response to a factor is seen is shown by a stepwise increases or decreases in the distance between the curves.

A notable change is evident in the transverse discrepancy with mesh tension, increasing the mesh tension increases the print distortion, *Figure 9*. It is postulated that this is a result of the higher mesh tension producing more deformation of the squeegee towards the end of the squeegee. This deformation produces a squeegee - screen interface where the friction in the transverse direction is lower and thus a greater proportion of the total extension is distributed in the mesh under the squeegee. The effect of mesh tension on the print direction distortion is consistent for all the columns of crosshairs in that a higher mesh increases the value of the discrepancy, *Figure 10*. It can therefore be concluded that higher mesh tension increases the drag force between the squeegee and the mesh.

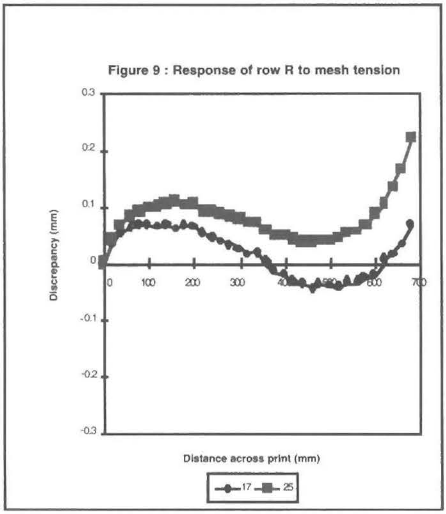


Figure 9 : Response of row R to mesh tension

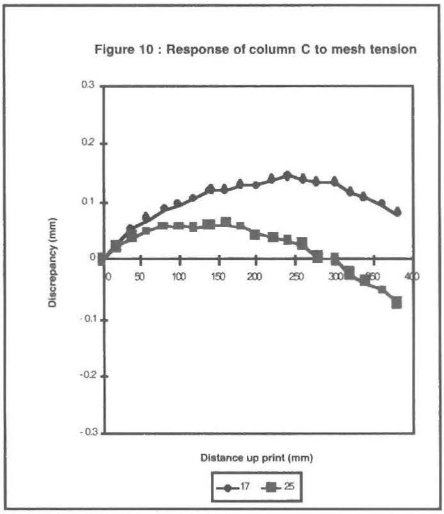


Figure 10 : Response of column C to mesh tension

A stepwise decrease in the transverse direction discrepancy is noticeable with increases in speed *(Figure 11)*, while increasing the print speed from 1000 to 2000 decreases the overall amount of print direction distortion while the increase in speed from 2000 to 2500 cph produces a negligible increase, *Figure 12*. The decrease in discrepancy between 1000 and 2000 cph may be related to the drag forces as the increase in shear rate changes the rheological characteristics of the ink. Although no firm conclusions can be drawn at this stage on the effect of print speed on the image distortion, it is clear that it may have considerable effect.

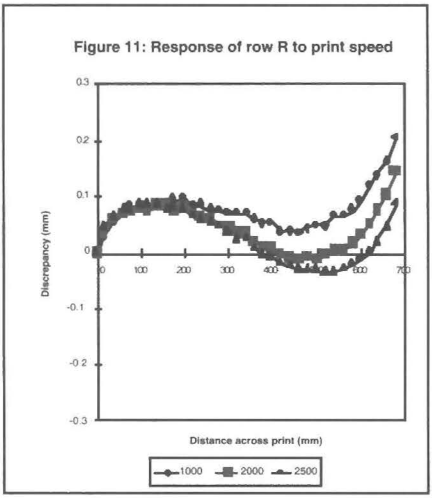


Figure 11: Response of row R to print speed

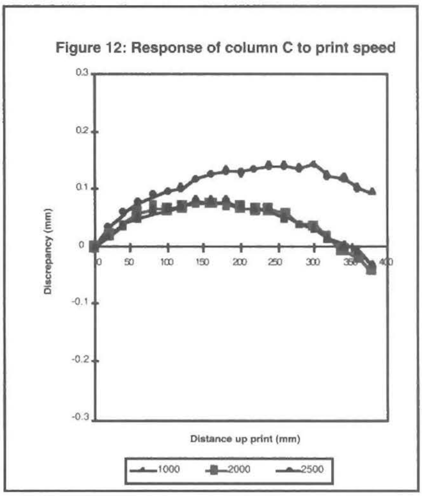


Figure 12: Response of column C to print speed

Mesh ruling has a non linear effect on the transverse distortion of the image, *(Figure 13)* however, little difference is observed in the print direction discrepancy between the 3 mesh rulings *(Figure 14)* , suggesting that the tensile and frictional properties of the meshes are different in the warp and the weft directions.

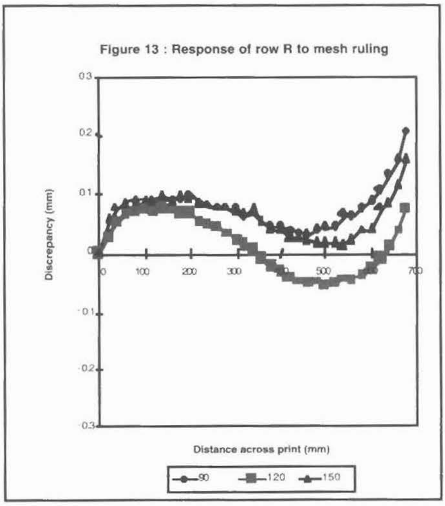


Figure 13 : Response of row R to mesh ruling

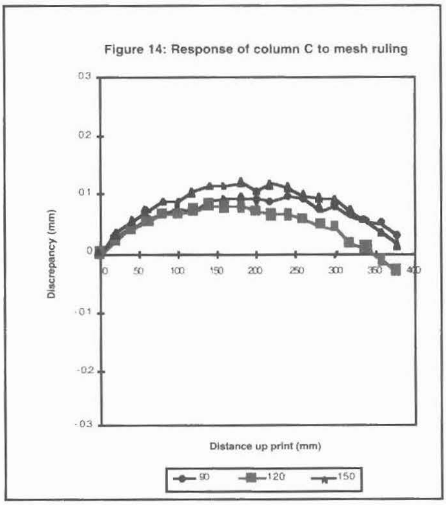


Figure 14: Response of column C to mesh ruling

The response of the transverse distortion to the squeegee angle *(Figure 15)* is unclear although it is believed to be linked to the transverse deformation of the squeegee leading to a change in the friction under the squeegee in a similar manner to the effect of mesh tension. The print direction distortion responds linearly to squeegee angle, although the magnitude of its effect is small, *Figure 16.*

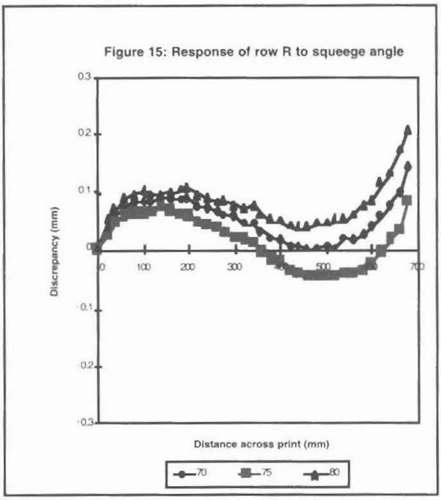


Figure 15: Response of row R to squeege angle

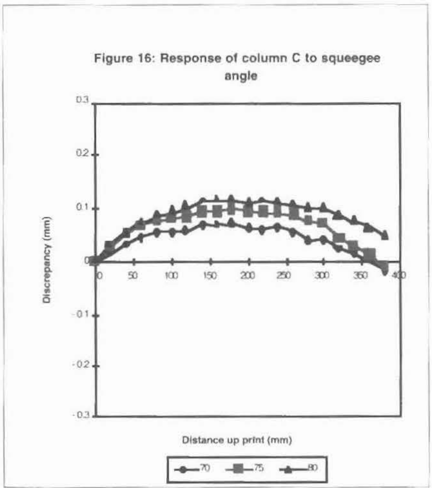


Figure 16: Response of column C to squeegee angle

The squeegee down pressure has a large effect on the transverse image distortion but its non linear response to the down pressure does not allow simple conclusions to be drawn *(Figure 17)*. It implies that the surface softness/ finish of the squeegee also plays and important role in deciding the distribution of extension in the screen. Similarly the response of the print direction distortion to the squeegee hardness - pressure term does not follow a simple linear trend, *Figure 18.*

Figure 17: Response of row R squeegee pressure - hardness

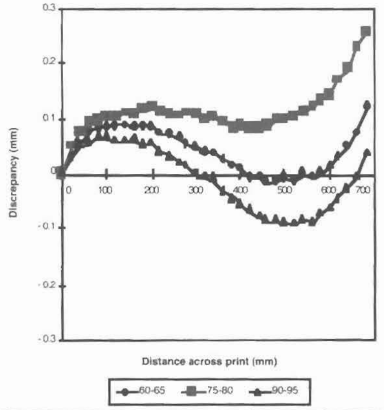
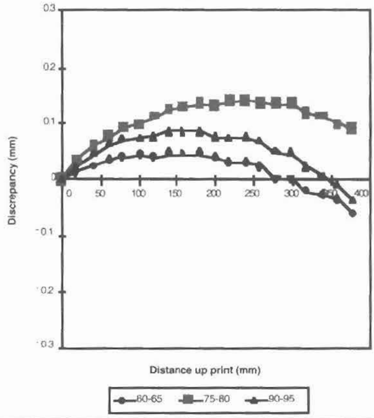


Figure 18: Response of column C to squeegee hardness - pressure



As a result of its rheological characteristics ink base also plays an appreciable part in deciding the transverse extension distribution in the screen, *Figure 19*. The ink also changes the print direction discrepancy *(Figure 20)* and is thought to be a result of the inks' rheological differences changing the frictional characteristics of the squeegee - screen interface.

Figure 19: Response of row R to ink base

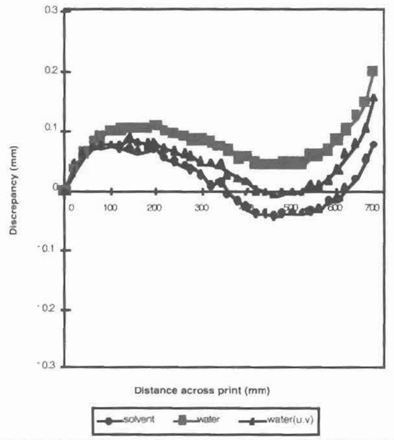
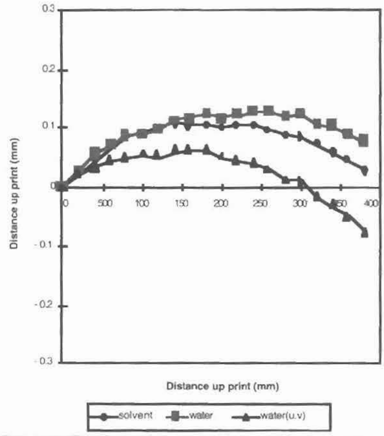


Figure 20: Response of column C to ink base



The ink type has a negligible effect on the transverse distortion *(Figure 21)*, and no effect on the print direction image distortion *(Figure 22)* which, being almost rheological identical, reiterates the importance of ink rheology and validates the overall experimental design.

Figure 21: Response of row R to ink type

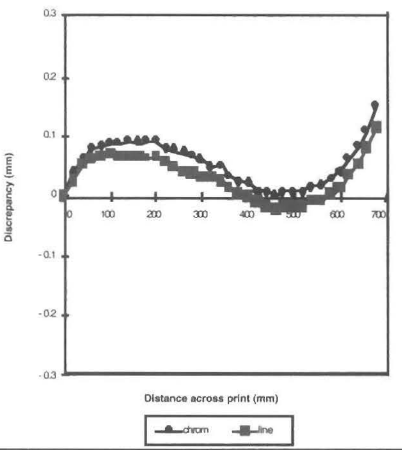
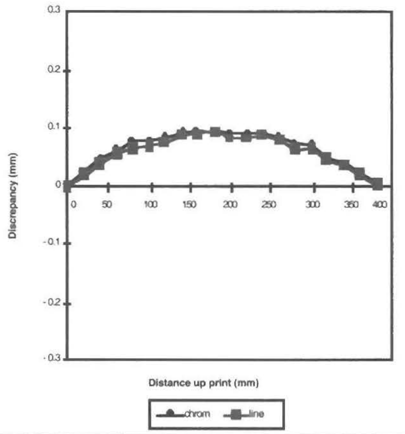


Figure 22: Response of column C to ink type



5. Discussion.

One of the most surprising findings of the experimental investigation was the image contraction, as shown by a negative discrepancy, sometimes observed in both the transverse and print directions. Closer inspection of the results showed that this was a result of the interaction of the image distortion in the two perpendicular directions. Where rapid image growth occurred in one direction, image contraction would tend to occur in the perpendicular direction. This is most noticeable on the edges of the print where the transverse strain is its highest resulting in columns A and G contracting. This phenomena may be attributed local distortion of the image where high local positive strains in one direction must be compensated for by negative strains in the orthogonal direction. Thus, while the 2 dimensional theoretical models show good agreement with the predicted distortion there is considerable interaction between the two directions.

The combination of the measurement and the model also indicate that limiting the distortion in both directions requires contradictory mesh - squeegee friction requirements. Ideally, high mesh - squeegee friction is required in the transverse direction while low friction is required in the print direction.

The maximum magnitude of the discrepancies measured in the transverse and print direction was 0.8 mm and 0.4 mm respectively. While these figures are not large a greater increase would be expected in large format 4 colour graphic printing. The comparatively small size of print, the controlled conditions of the experiment and the reinforced nature of the squeegee (which resists bending along the squeegee length, thus increasing squeegee end friction) would all tend to limit the distortion of the image.

A number of the parameters investigated in the orthogonal array clearly have a complex relationship with the image distortion. The successful prediction of the zero effect of the ink type and the agreement between the transverse distortion model and measurement show the validity of the experiment The non - Newtonian characteristics of ink and the compliant nature of the squeegee prevent any simple rules being drawn, a clear understanding of the distortion process in terms of press control parameters is a considerable challenge.

6. Conclusions.

A theoretical and experimental investigation into image distortion in the screen printing process has been carried out. The simple 2 dimensional theoretical models show reasonable comparison with that measured experimentally but they do not consider the considerable interaction between the image distortion in the two perpendicular directions.

While the orthogonal array experiment failed to identify a single controlling press parameter which dictates image distortion it has highlighted the complex relationship between the mesh, squeegee and ink which controls the mesh - squeegee frictional behaviour.

Finite element (FE) modelling of the fluid flow at the squeegee mesh interface and the mesh distortion is currently being used to extend the scope of the work so that a model of the process can be produced which includes the 3 dimensional nature of the mesh deformation and the friction related ink transfer.

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References.

1. W. Appleton, T.C. Claypole & E.H. Jewell, "The analysis of the image distortion in the screen printing process using the L18 experiment", DTI / Link project report "Improving the productivity of the screen printing process", 30/1/95.
2. Madhav S. Phadake, "Quality engineering using robust design", published by Prentice Hall International, ISBN 0-13-744723-X.
3. G. Taguchi and S. Konishi, "Taguchi methods. Orthogonal arrays and linear graphs", published by ASI press, 1987. ISBN 0-941243-01-X.
4.W. Appleton, T.C. Claypole & E.H. Jewell, "The application of orthogonal array analysis to the screen printing process.", 1995 European Taguchi methods and QFD symposium.
5. ISO / TC 130/WG 3 N 191 - "Title Graphic Technology: Process control for the manufacture of half tone separations, proof and production prints: Part 5 Screen printing".
6. E. Messerschmitt, "Rheological considerations for screen printing inks - Screen printing", September 1982, p 62-65.

Table 1: L_{18} Orthogonal array used for analysis purposes

Exp	Column							
	Mesh tension (N/cm)	Speed copies / hour	Mesh ruling threads/ cm	squeegee angle degrees	Paper	squeegee hardness - pressure	Ink	Ink type
1	17	1000	90	70	matt	60-65	solvent	chrom
2	17	1000	120	75	satin	75-80	water	chrom
3	17	1000	150	80	gloss	90-95	water (UV)	line
4	17	2000	90	70	satin	75-80	water (UV)	line
5	17	2000	120	75	gloss	90-95	solvent	chrom
6	17	2000	150	80	matt	60-65	water	chrom
7	17	2500	90	75	matt	90-95	water	line
8	17	2500	120	80	satin	60-65	water (UV)	chrom
9	17	2500	150	70	gloss	75-80	solvent	chrom
10	25	1000	90	80	gloss	75-80	water	chrom
11	25	1000	120	70	matt	90-95	water (UV)	chrom
12	25	1000	150	75	satin	60-65	solvent	line
13	25	2000	90	75	gloss	60-65	water (UV)	chrom
14	25	2000	120	80	matt	75-80	solvent	line
15	25	2000	150	70	satin	90-95	water	chrom
16	25	2500	90	80	satin	90-95	solvent	chrom
17	25	2500	120	70	gloss	60-65	water	line
18	25	2500	150	75	matt	75-80	water (UV)	chrom

Notes : Water = water based air dried (Sericol Aquacolour): Solvent = solvent based air dried (Sericol sericolour): water(UV) = water based UV cured (Sericol Aquaspeed)

Table 2: Standard conditions.

Parameter	Value
Mesh / stencil types	Satti coloured polyester, Autotype Capillex capillary film stencil.90 T XR 15, 120 T XR20, 150 T XR15
Press type	Sakurai, Automatic Cylinder.
Squeegee length.	Print size + 25 mm either side, total length 870 mm, rounded ends with 10 mm radius.
Snap off gap	3 mm.
Mesh angle	90^{o} ,warp in print direction.

Table 3 : Summary of results from orthogonal array analysis.

Factor.	Transverse distortion.	Print direction distortion.
Mesh Tension.	Increases with increasing mesh tension increases.	Increases with increasing mesh tension increases.
Print speed.	Linear decrease with increasing print speed.	Decrease between 1000 and 2000 cph, no change 2000 to 2500 cph.
Mesh Ruling.	Noticeable Non linear effect.	Little effect.
Squeegee angle.	Noticeable Non linear effect.	Small linear effect.
Squeegee hardness / pressure term.	Large non linear effect.	Large non linear effect.
Ink base.	Considerable effect.	Considerable effect.
Ink type.	Negligible effect.	No effect.