PHYSICAL AND OPTICAL BEHAVIOR OF LINE PAIRS IN GRAPHIC ARTS MEDIA

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Abstract

This study was made for the purpose of characterizing image sharpness through the different graphic arts media: film, plate, proof, and print. A model was proposed for evaluating sharpness with a densitometer. This paper discusses how line pairs of varying spatial frequency image in different media. Sharpness as calculated from optical measurements did not always agree with the subjective impression of edge sharpness. The reason for this can be explained by diffraction in the high frequency elements, and light scatter when measurements are made with a reflection densitometer.

The paper will begin by describing the target and theory of operation. Behavior of three different films will follow. Sharpness of two photomechanical proofing systems will be compared to that of ink and paper. Finally, an attempt to use the line elements as a run control target will be described.

Description of the Target and the Model

A standard method for measuring acutance or "sharpness" is described in the SPSE Handbook of Photographic Science and Engineering (Ref. 1). The acutance is calculated from microdensitometric traces across a sharp edge image. Microdensitometers are rare in the printing industry but reflection densitometers are common. A test image (Ref. 2) has been designed by Anthony Stanton and Richard D. Warner which claims to provide the printer with an alternative way for evaluating sharpness with a transmission or reflection densitometer.

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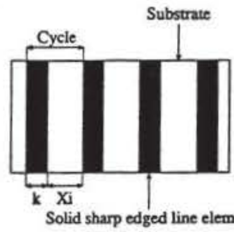
The test image is composed of 15 micron line elements varying in the frequency with which they occur. The test image is called the GATF Frequency Modulated Acutance Guide (FM Target). There are 12 frequencies on the FM

Figure 1. Enlarged segment of the imaged GATF Frequency Modulated Acutance Guide



target ranging in 100 cycle intervals from 300 to 1400 cycles per inch. A cycle is a line space pair (Figure 1). The higher the frequency, the smaller the space between the lines (Table 1). There are two orientations of the line patterns perpendicular to each other to show any directional effects influencing the target, especially in printing. Assuming that each micro line has the same infinitesimal solid density as a large solid, and knowing the line width (k) and the density of the substrate, the theoretical density for each frequency can be determined. The fractional area occupied by a line element for any given frequency is kf(i) and the fractional area occupied by the space is (1-kf(i)). The reflectance of a line pair at any frequency is given by: $R=10^{-Dp}(1-kf_i)+10^{-Ds}kf_i$
where D_p is the density of the substrate and D_s is the density of the solid area. For negative films duplicated from the master, D_p should be taken equal to the black density and D_s should be taken equal to the density of the clear film itself. The theoretical density of any frequency is given by:

$$D_{theo}=-Log_{10}(10^{-Dp}(1-kf_i)+10^{-Ds}kf_i)\ (i).$$

Any distortion or growth around the edges of the line elements should affect the measured density. The ratio between the measured density and the theoretical density should give an idea of image quality deterioration. The ratio should remain constant through the range of frequencies for which one can still distinguish dark lines from light spaces under a reasonable magnification (60x). It should be close to one if the lines are sharp and greater or less than one if the lines are not sharp. For the calculation of the theoretical densities, it is important to keep units consistent. If the frequency is in cycles per inch, the line width k should be in inches.

Table 1. Spaces between 15 micron lines on the glass master.

fi in cycles/inch	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Xi in µm	69.7	48.5	35.8	27.3	21.3	16.8	13.2	10.4	8.1	6.2	4.5	3.1
Xi in inches $\times 10^{4}$	27.4	19.1	14.1	10.7	8.4	6.6	5.2	4.1	3.2	2.4	1.8	1.2

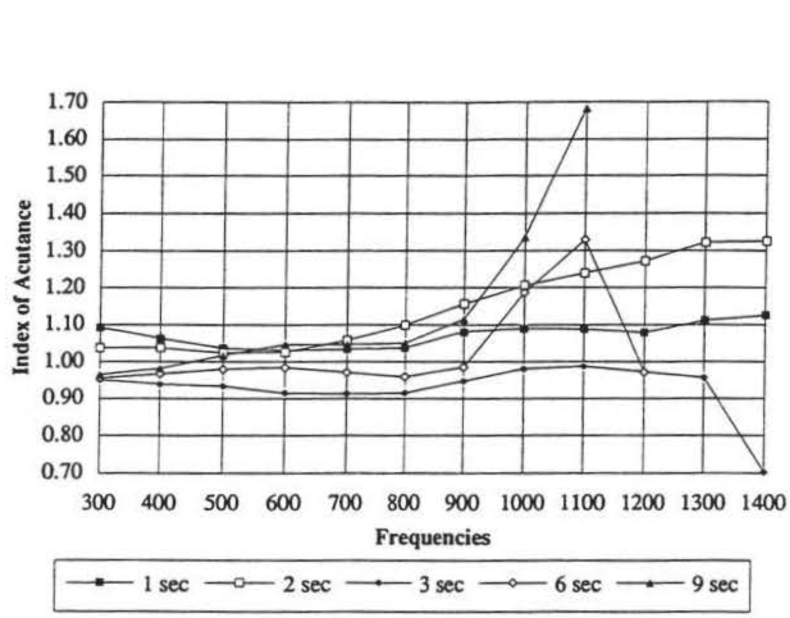


Figure 2. Index of acutance for the film A and horizontal lines

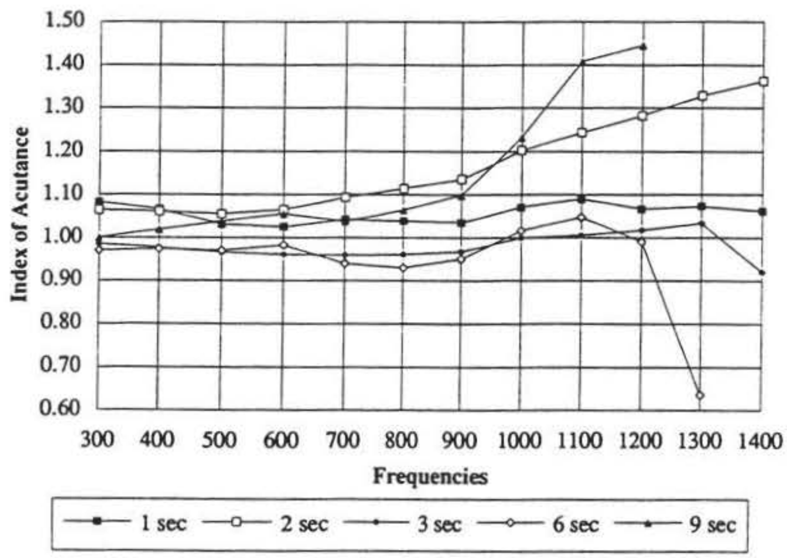


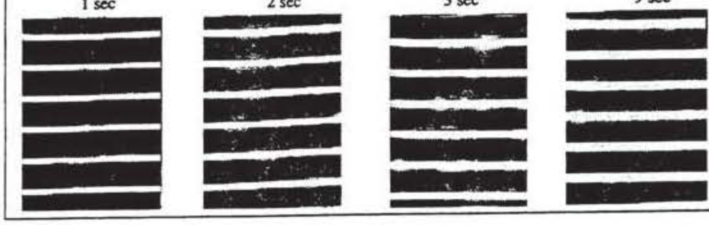
Figure 3. Index of acutance for the film A and vertical lines

Behavior of Three Different Duplicating Films

The first medium that was studied was duplication. The original glass master was imaged on three different films A, B, and C with an open frame exposure unit and different times of exposure: 1, 2, 3, 6, and 9 seconds.

The first method that was used to determine the index of acutance was described in the 1991 TAGA Proceedings. The line width was assumed to be equal to 15 microns (0.00059in) if all the frequencies were resolved. Otherwise the line width was determined from the frequency f_{max}. F_{max} is the highest frequency at which lines are resolved. The ratios between the measured densities and the theoretical densities were plotted for each frequency for a given film, for a given time of exposure and type of line. As can be seen in Figure 2 and Figure 3, strange curves were obtained and the ratio did not remain constant through the frequency range except for certain times. The principal reason for this was that the correct line width was not used in the formula. Even though lines are still visible from 300 to 1400 cpi, the line width was not necessarily 15 microns. The width increased with the time of exposure as can be seen in the photomicrographs taken of film A at 200X and a frequency of 300 cpi in Figure 4.

Figure 4. Photomicrographs of vertical lines on the film A for different times of exposure:



Although a "straight line" was obtained, the index of acutance of the highest frequency was dropping. This could be due to the fact that the black lines were no longer composed of a solid core, and the lines were not sharp. Since the densities at high frequencies were lower, an error of the line width determination may also result in a drop of the index of acutance. For example, the differential of D_{theo} as a function of k is as follows:

$$\frac{\partial D_{theo}}{\partial k} = -\frac{1}{\ln(10)} \times \frac{f_i\left(10^{-D_s} - 10^{-D_p}\right)}{10^{-D_p}(1-kf_i) + 10^{-D_s} kf_i}$$

In the case of the film Ds<<Dp and therefore $10^{-D_s} >> 10^{-D_p}$. The differential can be rewritten :

$$\frac{\partial D_{theo}}{\partial k} \approx -\frac{10^{-D_s} f_i}{10^{-D_p}(1-kf_i) + 10^{-D_s} kf_i} \times \frac{1}{\ln(10)} \approx -\frac{1}{\ln(10)} \times \frac{1}{k} \text{ (ii)}$$

Then $\Delta D_{theo} \approx -\frac{1}{\ln(10)} \times \frac{\Delta k}{k}$ (iii) is independent of the frequency with this hypothesis.

From this "computed" k, the graphs plotted before were remade. As can be seen in Figures 6 and 7, the plots line up on a straight line. It is even more visible for films B and C. The indices of acutance are given in Table 2.

Table 2. Indices of acutance calculated for these three films.

	Film A		Film B		Film C	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
1 sec	1.03	1.06	1.34	1.35	1.39	1.4
2 sec	0.94	0.98	1.05	1.05	1.05	1.07
3 sec	0.94	0.97	0.91	0.98	0.94	0.98
6 sec	0.93	0.98	0.8	0.88	0.78	0.88
9 sec	0.90	0.95	0.81	0.91	0.7	0.78

The question now was whether or not the numbers represented the sharpness of the lines. Several pictures of the vertical lines were taken at a constant frequency of 300 cycles per inch to verify this. The three films were imaged under a magnifying factor of 200X (Figure 8). By looking at the pictures, it was hard to believe that Film A was much sharper than film B and C. Even if there were more bubbles in films B and C, the lines looked sharp. The trend for all the films was to have an index decreasing with the time of exposure as well as the last frequency visible (Table 3). This target showed here that Film A was less sensitive than films B and C to the time of exposure, and that A could resolve higher frequencies. Films B and C showed the same behavior; the only difference between them was their thickness, film C was thicker than film B. These films seemed to give the same index of acutance except for a time of 9 sec. For this time of exposure and for the three films, pictures of vertical lines at 1100 cycles per inch were taken under a 200X magnification (Figure 8). By comparing these pictures with those taken previously, it can be seen that the widths of the lines at 300 cpi and 1100 cpi for the same film and the same time of exposure were no longer the same. The difference, Line width (300) - Line width (1100), increased with the time of exposure.

Table 3. Higher frequencies resolved on the three different films.

	Film A		Film B		Film C	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
1 sec	1400	1400	1400	1400	1400	1400
2 sec	1400	1400	1400	1400	1300	1400
3 sec	1400	1400	1200	1300	1200	1300
6 sec	1200	1300	1100	1200	1100	1200
9 sec	1100	1200	1100	1100	1100	1100

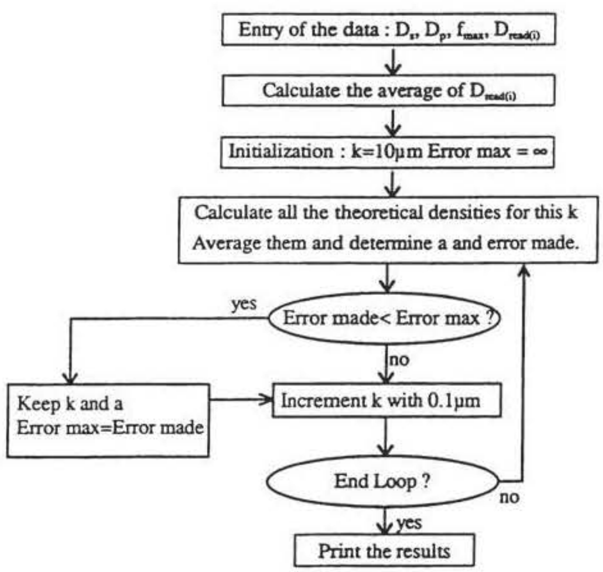
Therefore, if the line width was underestimated by 1 micron and it really measured 16 microns instead of 15 microns, by using the formula (iii) the theoretical density should decrease by 1/(2.3x15). For the data of film A (horizontal lines, time of exposure of 3 sec and f(i)=1400) $D_{measured}$=0.078,D_p=5.775,D_s=0.028:

-if k=15 microns then D_{theo}=0.111 and the index is 0.70
-if k=16 microns then D_{theo}=0.083 and the index is 0.94

A difference of 1 micron in the line width resulted in a change of 0.24 of the index of acutance. In the case of negative duping films, the higher the frequency, the lower the density and therefore the more sensitive to the line width. This suggests how critical the line width is for the calculations of sharpness on film.

Even if a "straight line" was obtained for the ratio plot, it seems that each frequency has a different index of acutance. Should the index be the average? For this reason a new way to determine the characteristic of sharpness was considered. The approach taken was to try to correlate the set of theoretical densities calculated with the formula (i) and the set of measured densities for the correct range of frequencies with the least square method and assuming an intercept of zero. The index of acutance was defined as the best slope for k varying between 10 microns and the maximum possible ($1/f_{max}$). A short algorithm is given in Figure 5.

Figure 5. Algorithm.



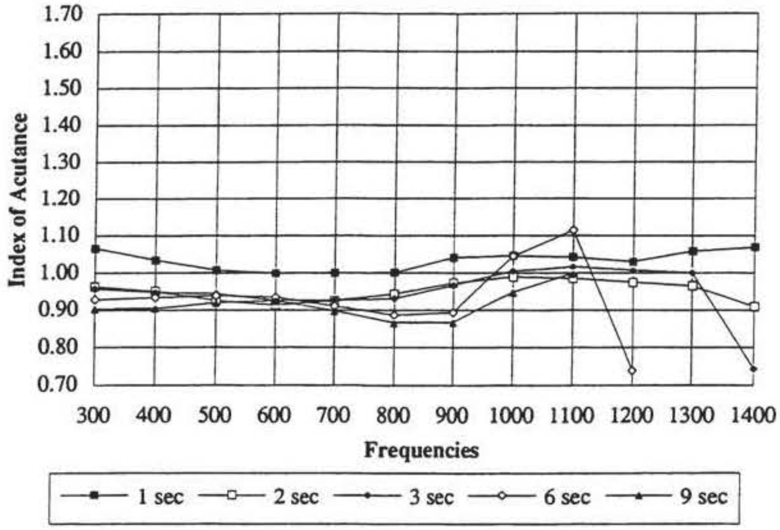


Figure 6. Index of acutance for the film A and horizontal lines (optimized)

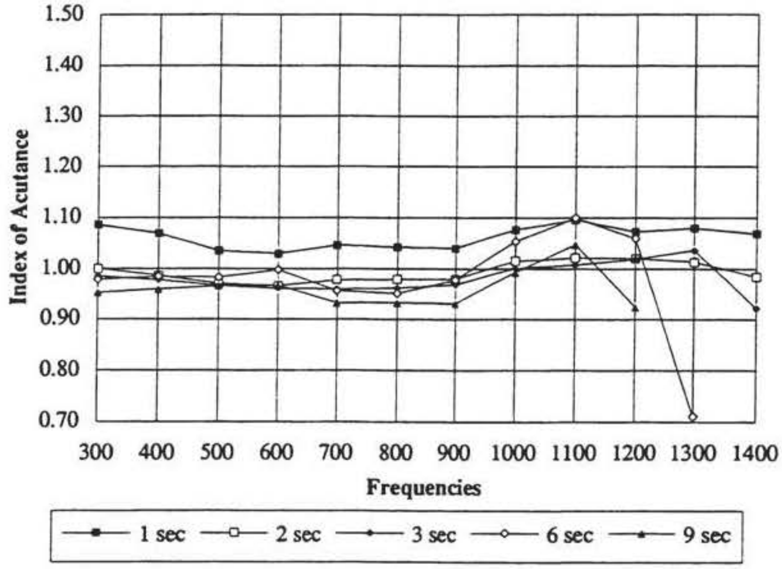
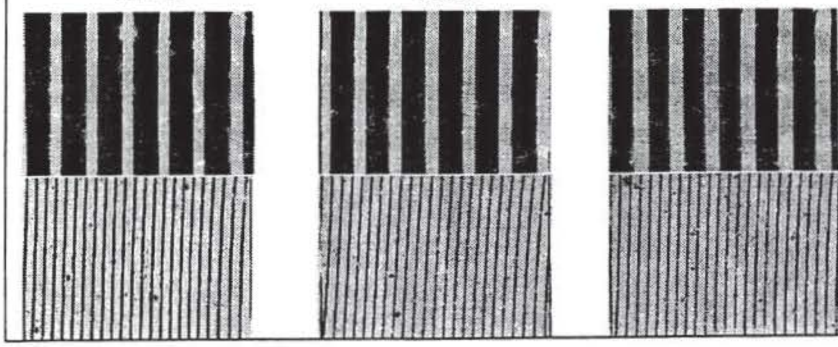


Figure 7. Index of acutance for the film A and vertical lines (optimized)

Figure 8. Photomicrographs of vertical lines on films A,B and C for a constant time of exposure of 9 sec and two different frequencies 300 and 1100 cpi :



The line width varied through the frequency range, due to diffraction effects. As described before, the determination of the line width was critical in higher frequencies and could result in a change of 0.2 of the index of acutance. The least square program was looking for the best index of acutance computed from a **unique** line width and it was not the case. An index of 0.7 was probably not so bad by comparison with 0.9 for the sharpness but this also represented the "diffraction" effect.

From this point, the "2 sec" film A was used to make plates and print the different papers, because it gave the best indices and was showing less differences in line widths through the frequency range.

Results of the Tests Made on Different Proofing Systems and on Press

Film A, imaged at 2 sec, was imaged on two photomechanical proofing systems D and E. The densities through the range of frequencies were measured with a Cosar 205 status T densitometer. The most critical part at this stage was to determine the frequency maximum, especially for the yellow. A 60x magnifying glass was used for this purpose. The criterion was to determine whether or not a frequency was resolved. The spaces between the printed or proofed lines should not be broken. Once f(max) and the densities were known the program was executed. The black densities used for calculations for both proofing systems are given in Table 4.

Table 4. Black Densities on the two proofing systems.

f(i) in cycles/inch	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Proofing system D												
Vertical lines	0.27	0.35	0.43	0.51	0.60	0.69	0.80	0.90	1.03	1.18	1.32	<u>1.42</u>
Proofing system D												
Horizontal lines	0.29	0.37	0.47	0.56	0.66	0.75	0.85	0.95	1.05	1.21	<u>1.34</u>	1.57
Proofing system E												
Vertical lines	0.30	0.39	0.49	0.69	0.93	1.11	1.25	1.35	1.45	<u>1.58</u>	1.68	1.68
Proofing system E												
Horizontal lines	0.33	0.43	0.56	0.80	1.04	1.19	1.32	1.38	1.48	<u>1.58</u>	1.66	1.69

The solid densities were respectively 1.90 and 1.69 for D and E and the densities of the paper were 0.11 and 0.04. The underlined densities indicate f(max) in each case. The program with those data calculated the following optimum values for the densities in Table 4.

Table 5. Optimum indices of acutance for the two proofing systems.

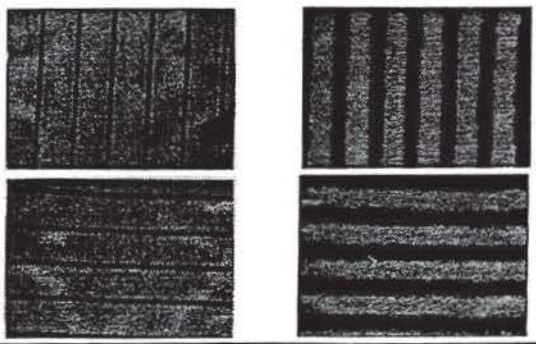
Proofing system D:	Vertical lines	k=14.9 microns a=1.79
	Horizontal lines	k=15.2 microns a=1.85
Proofing system E:	Vertical lines	k=13.8 microns a=3.46
	Horizontal lines	k=11.9 microns a=4.36

Proof E looked visually less sharp than proof D in the pictures taken after magnification (200X) (Figure 9). The numbers seem to confirm the visual impression, but the line width computed is not quite real. Once again it is an average as explained before and the program was calculating the best regression line. The index of acutance obtained for proof D should have been closer to one. The line widths were measured on the pictures for proof D for both horizontal and vertical lines at 2 mm for a frequency of 300 cpi. The real magnifying factor is equal to 180X and this distance represented 11.1 microns. With the frequency of 300 cpi, the theoretical density should have been Dtheo=0.17, and the densitometer was reading 0.27. The index of acutance should have been 1.59, which is not one even though the lines were sharp.

This suggested that optical characteristics were interfering with the measurement of sharpness. The reflection densitometer was integrating and was reading higher densities. The light was penetrating into the paper and being

Figure 9 Photomicrographs of vertical and horizontal lines on both proofing systems D and E:

Proofing System D — Proofing system E



trapped under the line elements (Ref. 3). There was also density increase due to gloss. To verify this fact, a plastic sheet was laminated on a printed board sample on which the acutance target was printed with ink. The black densities measured with the densitometer are displayed in Table 7. The density of the paper increased from 0.09 without the plastic to 0.12 with the layer. The f(max) did not change. The results calculated by the program are shown in Table 6.

Table 6. Optimum indices of acutance for the board with and without layer.

Board w/o layer:	Vertical lines	k=28.1 microns a=1.19
Board w layer:	Vertical lines	k=24.0 microns a=1.69

Table 7. Black densities on the board with and without layer.

fi in cycles/inch	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
Board w/o layer												
Vertical lines	0.29	0.38	0.49	0.63	0.77	0.88	0.96	1.00	1.05	1.19	1.29	1.29
Board w layer												
Horizontal lines	0.42	0.53	0.66	0.78	0.93	1.03	1.11	1.16	1.20	1.34	1.48	1.48

On the picture in Figure 10 a coarse line width of 0.5mm was measured with the real magnifying factor of 180X, and found to be 27.8 microns. From this data, the theoretical densities in both cases could be calculated for 300 cpi:

Board w layer	Dtheo=0.28 a=1.68
Board w/o layer	Dtheo=0.25 a=1.16

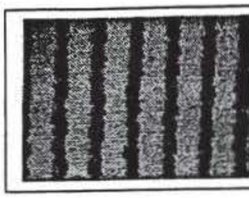


Figure 10
Photomicrographs of vertical lines on the board.

Although the lines are not sharp in the pictures, the index of acutance is close to one. The core of the line is not completely black, probably due to the emulsification of the ink, and the density is lower than it should be.

These two experiments suggest that the densitometer is not the right instrument for measuring the sharpness of the lines because of the light scattering and therefore the optical gain generated.

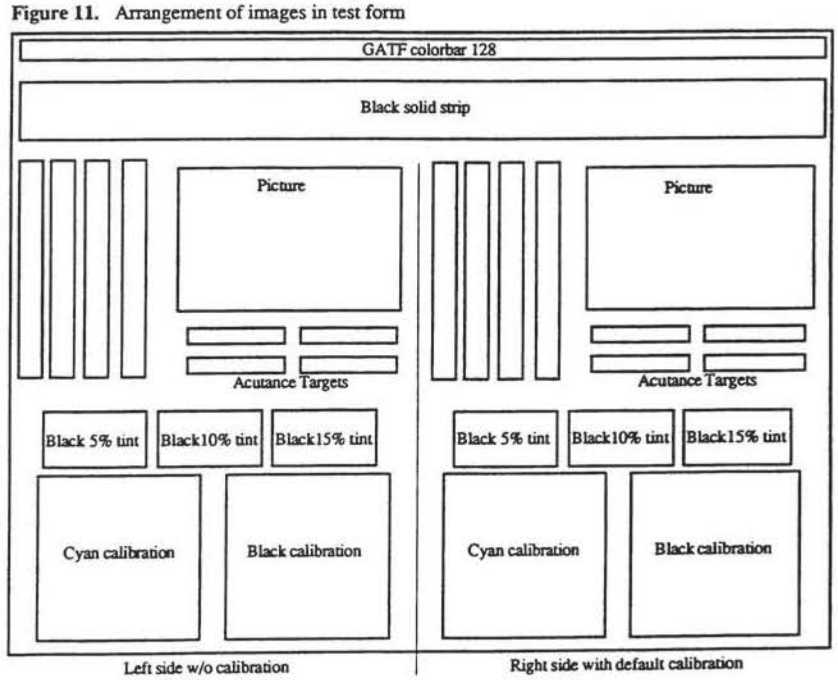
A press test was run to further evaluate the behavior of this target. The goal was to determine the influence of ink densities on the indices and also to see if the target could point to optimum inking. The film used was still film A, but this time the duping was made on a standard vacuum frame. The draw down time was 120 sec to insure a proper contact between the master and the film. The exposure time was 6 units using low intensity. Under those conditions, there were still both vertical and horizontal lines at 1400 cpi giving indices respectively of 0.93 and 0.90. The film was used to burn 3M Viking pre sensitized negative plates. Once again the draw down time was doubled to insure the transfer of the lines onto the plate. Since the 6 micron lines were broken on the UGRA plate control wedge (Ref. 4), the range 1200 cpi to 1400 cpi was no longer visible. Indeed the spaces between the lines for those frequencies are less than 6.2 microns (see Table 1). The plates were printed on a Heidelberg 4 color $20^{1/2}$x$28^{3/8}$ inch lithographic press on #3 coated paper with " typical" offset inks. This target was printed in four colors at two different places on the sheet (see Figure 11).

The first step during the test was to register the pictures and find the balance for the lower level of ink densities called level 0. From this step, the ink densities were progressively increased to get 10 different stages from level 0 up to level 9. The solid densities are given in Table 8. Twenty-five sheets were taken for each level and the densities were measured with a Cosar Autosmart status T densitometer and averaged. The highest frequency still visible was evaluated for all colors except yellow and the acutance calculations were tabulated in Table 9.

Table 8. Solid densities printed for each level and each side of the sheet.

	Left side				Right side			
	Black	Cyan	Magenta	Yellow	Black	Cyan	Magenta	Yellow
Level 0	1.12	0.84	0.78	0.53	1.13	0.78	0.94	0.61
Level 1	1.17	0.89	0.94	0.68	1.17	0.91	0.94	0.75
Level 2	1.27	0.97	0.97	0.73	1.29	1.00	0.99	0.88
Level 3	1.32	1.08	1.09	0.81	1.32	1.15	1.11	0.95
Level 4	1.37	1.24	1.19	0.79	1.38	1.30	1.16	0.92
Level 5	1.40	<u>1.35</u>	1.27	0.80	1.44	1.38	1.28	0.92
Level 6	1.43	1.37	<u>1.30</u>	<u>0.83</u>	1.46	1.38	1.29	1.00
Level 7	1.52	1.42	1.45	1.12	1.56	1.50	1.51	1.15
Level 8	<u>1.58</u>	1.58	1.57	1.26	1.66	1.60	1.65	1.24
Level 9 *	1.71	1.60	1.71	1.42	1.72	1.71	1.78	1.29

Figure 11. Arrangement of images in test form



The underlined numbers indicates the normal inking level used on the press when printing coated stock.

The numbers given in Table 9 remain quite constant for all colors and over all ink density levels. Those numbers don't seem to be able to characterize the best densities to be run on a press for a given ink and paper couple and if this target is measuring the sharpness, it means that sharpness is not influenced by the amount of ink put on the paper. The dots are growing in size but their edges remain the same. This target may be useful for observing the maximum frequency still visible. The higher frequency is decreasing as the ink density and dot gain are increasing. The horizontal lines are not only influenced by the dot gain but also by slurring and should therefore plug quicker than the vertical lines. That is confirmed for almost all the colors.

Table 9. Indices of acutance calculated for each level and each color except yellow.

Levels		#0	#1	#2	#3	#4	#5	#6	#7	#8	#9
Black Ver(L)	fmax	900	900	900	900	800	800	800	700	600	600
Black Ver(L)	**Index**	**1.62**	**1.67**	**1.70**	**1.73**	**1.55**	**1.57**	**1.69**	**1.44**	**1.54**	**1.41**
Black Hor(L)	fmax	900	900	900	900	800	800	700	700	600	600
Black Hor(L)	**Index**	**1.71**	**1.65**	**1.66**	**1.71**	**1.66**	**1.60**	**1.87**	**1.85**	**1.56**	**1.71**
Cyan Ver(L)	fmax	900	900	800	800	700	700	700	700	700	600
Cyan Ver(L)	**Index**	**1.61**	**1.66**	**1.64**	**1.66**	**1.65**	**1.60**	**1.93**	**1.69**	**1.91**	**1.73**
Cyan Hor(L)	fmax	900	800	800	800	700	700	700	600	500	500
Cyan Hor(L)	**Index**	**1.58**	**1.49**	**1.49**	**1.64**	**1.76**	**1.57**	**1.98**	**1.71**	**1.85**	**1.77**
Mag Ver(L)	fmax	1000	900	900	900	800	800	800	700	700	700
Mag Ver(L)	**Index**	**1.63**	**1.38**	**1.39**	**1.42**	**1.38**	**1.44**	**1.48**	**1.35**	**1.29**	**1.36**
Mag Hor(L)	fmax	1000	900	900	900	800	800	700	700	700	600
Mag Hor(L)	**Index**	**1.67**	**1.52**	**1.49**	**1.66**	**1.54**	**1.63**	**1.77**	**1.56**	**1.86**	**1.85**
Black Ver(R)	fmax	900	900	900	900	800	800	700	600	600	600
Black Ver(R)	**Index**	**1.77**	**1.82**	**1.81**	**1.86**	**1.71**	**1.76**	**1.45**	**1.35**	**1.53**	**1.61**
Black Hor(R)	fmax	900	900	900	900	800	800	700	600	600	500
Black Hor(R)	**Index**	**1.84**	**1.83**	**1.81**	**1.87**	**1.71**	**1.73**	**1.56**	**1.39**	**1.58**	**1.65**
Cyan Ver(R)	fmax	800	700	600	600	600	600	600	600	500	500
Cyan Ver(R)	**Index**	**1.67**	**1.69**	**1.59**	**1.59**	**1.71**	**1.62**	**1.68**	**1.75**	**1.82**	**1.76**
Cyan Hor(R)	fmax	700	700	600	600	600	600	600	600	500	500
Cyan Hor(R)	**Index**	**1.38**	**1.44**	**1.19**	**1.26**	**1.22**	**1.21**	**1.38**	**1.48**	**1.47**	**1.37**
Mag Ver(R)	fmax	900	900	900	900	800	800	800	700	700	700
Mag Ver(R)	**Index**	**1.72**	**1.74**	**1.71**	**1.82**	**1.53**	**1.59**	**1.61**	**1.38**	**1.55**	**1.57**
Mag Hor(R)	fmax	900	900	900	900	800	800	800	700	600	600
Mag Hor(R)	**Index**	**1.79**	**1.80**	**1.68**	**1.85**	**1.67**	**1.78**	**1.76**	**1.71**	**1.43**	**1.42**

Conclusion

This technique shows some encouraging results when used on the films, and as demonstrated, small differences in indices are indicating more the diffraction effects than a difference of sharpness. However, on printed sheets and proofing systems, because of optical properties of the substrate involved in the density measurements, this method does not allow the printer to compare the sharpness of the dots in two different media. The percent coverage of the lines in the film can be calculated for each frequency by assuming a line width of 15 microns and using the formula: $a\% = \frac{0.15 \times f_i}{2.54}$

Table 10. Percent coverages of the lines for each frequency.

f(i) in cycles/inch	300	400	500	600	700	800	900	1000	1100	1200	1300	1400
area, %	18%	24%	30%	35%	41%	47%	53%	59%	65%	71%	77%	83%

The mechanical dot gain is a function of the perimeter of the lines and should increase through the range of frequency whereas the optical dot gain depends on percent coverage and the substrate. The numbers calculated by the program are not comparable from one paper to another or one proof to another.

This device may be useful as a resolution target using f(max) even if it was not the original purpose, and it is showing directional effects influencing the printing quality. There may be an application as a plate control wedge and further studies should be done in this field. In this case, density measurements are impossible and the analysis should be by visual inspection.

Literature Cited

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