IMAGE QUALITY, CONTRAST TRANSFER AND TONE REPRODUCTION

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Abstract: Tone Reproduction Curve (TRC) of an imaging system is an accepted way to describe its quality capabilities. Such applications were first developed in Photo Science for tonal images and then applied in Graphic Arts for halftones. The TRC is, in a sense, a description of a system in an amplitude domain of densities. Conventional attributes of halftone imaging systems (*i.e.* dot gain, print contrast) use the TRC for their definitions. Recently, descriptions in a spatial frequency domain became useful tools in image quality assessment. One of them, the Contrast Transfer Function (CTF), led to a single number quality merit factor (QF) for halftone imaging systems. The QF number describes overall image capabilities and can be measured for ink - paper - press, plates, proofing, *etc.* The integral character of the QF number apparently is masking conventional attributes of imaging systems. Current study connects the CTF with a TRC of a halftone imaging system. It shows, how a TRC for an arbitrary screen frequency can be evaluated from the measured CTF. The applied value of the study is in a procedure for adjusting a scanner to fit a given ink - paper - press performance.

Introduction

Tone Reproduction Curves (TRC) are a well established tool for analysis of printing systems. Its popularity in the graphics art community is wide spread. The topic of TCR was frequently discussed on technical meetings [1]. See Figure 1 for illustrations. Practically every test form has patches for evaluations of the TRC. Computational procedures are relatively simple and well defined. However, the relatively large number of patches required for a reasonably confident evaluation of TRC remains an obstacle for daily use of the TRC for printing process control.

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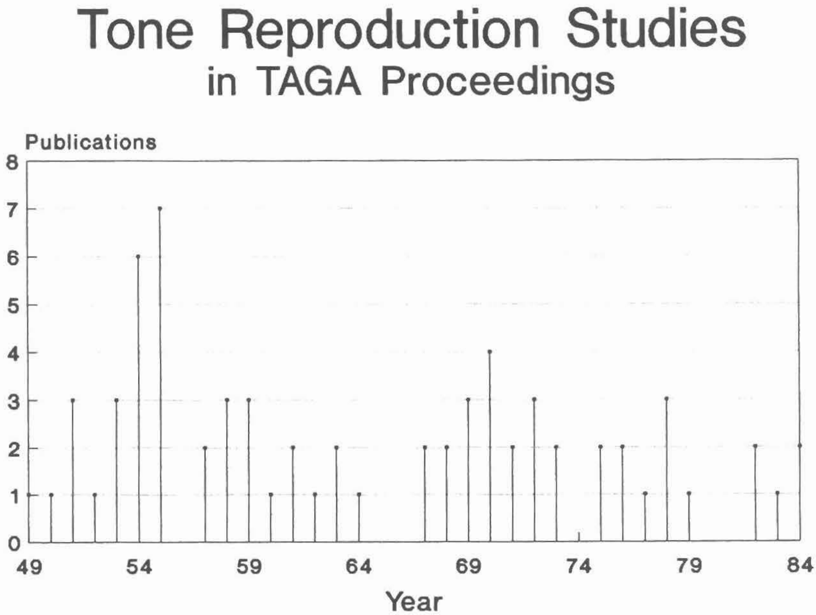

Figure 1.

Current study reports our attempts to find an alternative way for evaluation of a printing system performance. For several years we have been developing methods based on spatial characteristics of a printing system. One of them describes its ability to deliver image contrast -- the Contrast Transfer Function (CTF). We measure this ability in a necessary range of spatial frequencies imbedded in the GURLAB™ Target, shown on Figure 2. Every patch of the Target is a Rhonchi ruler or 50% line screen with a known number of lines/inch.

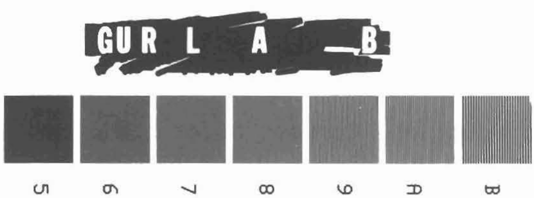

Figure 2. Part of the Target for CTF measurements.

The actual size of the Target can be compatible with the size of popular color bars. The Target can be placed practically in every inking key zone across the web taking about an inch space for four colors. We used a 3.8 mm aperture reflection densitometer as a part of the GURLAB™ System for Image Quality Measurements to determine the CTF.

The advantage of using the CTF is in its ability to generate a single number of quality measure. It is the measure of a printing system performance. This number correlates with the human perception of image quality, while the majority of the conventional parameters (dot gain, print contrast, etc.) are only the process variables.

Two approaches -- CTF and TRC -- are complementing each other in general. We observe it in Optics and Photo Sciences. The TRC describes the system's ability to transfer tonal information only, regardless of the size of image area. Size dependant or spatial properties are associated with the CTF. By definition, the CTF is a function in the domain of spatial frequencies. It describes the ability of the imaging system to deliver tonal variations for different sizes of these variations. Such image attributes as image sharpness, edge definition, resolution of fine details are CTF dependant. G. Jorgensen mentioned the validity of this in 1960 for halftone images [2]. In his later work [3] he used the GATF Star Target and an elaborate micro densitometer to describe spatial properties by Reflective Density Transfer functions. His functions are similar to the Contrast Transfer in their behaviour.

The specific structure of halftone images allows one to connect the CTF and the TRC description for a conventional printing system. Our study concludes that Tone Reproduction Curves can be calculated from the measured CTF. For printing systems, the CTF description is more general than the TRC. One measured CTF can generate TRCs for any given screen frequency.

Variety of Tone Reproduction Curves

Tone Reproduction Curves have their origin in the sensitivity curves introduced in B/W photography. Known as H&D curves, they are a method for characterizing the emulsions [4]. H&D curve describes a connection between the amount of light (exposure) and the resulted blackness of a negative film. Optical density d is a quantitative measure of this blackness. By its definition, transmission density

$$d = -\log_{10} [I_0 / I_i], \qquad (1)$$

where I_0 is the flux that comes out after the film, illuminated with the incident I_i flux [5]. Later, the density definition (1) was expanded to include reflective materials by standardizing the angles of incidence, reflectance and spectral response of the instrument [6]. In printing, the reflective densities became quantitative measures of the ink film thickness. They describe the changes in incident and reflected intensities according to the equation (1). These changes resulted from the ink deposition on the paper's surface.

Soon, the H&D curves survived a serious modification. The purpose of it was to fit the demands of Image Science, and to help in understanding the mechanisms of generalized two dimensional image making. It was generated by a system approach to an image process. We found certain convenience in presenting such a process as a transfer of an input image (original) through an imaging system to create an output (copy). This symbolic description was equivalent to a transform of original densities to the densities of a copy. The Tone Reproduction Curve was a function describing output densities generated by known densities on input.

Halftones caused the next modification of the TRC. By its nature, a halftone picture is a binary image (ink on, ink off) in the *micro* sense. The variation in size of the halftone dot, spaced periodically in two dimensions, creates the integrated *macro* variations of the reflected density. The macro density will be a function of a solid cover density, of cause. To avoid it, the TRC can be plotted in a space of tints -- per cent values of solid covers. Horizontal axis in this space is usually a tint value T_i on a film (desired, input). Final image density D_t can be measured by a reflective densitometer. It is easy to calculate the effective value of the tint T_0 (observed, output) once the densities of solid cover d_b and clear paper d_w are known:

$$T_0 = (\text{pow}[-D_t] - \text{pow}[-d_w])/(\text{pow}[-d_b] - \text{pow}[-d_w]), \qquad (2)$$

where $\text{pow}[x]=10^x$. Expression (2) is equivalent to the Murray-Davies equation, published first in 1936 [7].

Developments of the dot gain concept in printing led to another convolution of the TRC. Instead of $T_0 = f(T_i)$, the same results can be plotted as

$$T_0 - T_i = f(T_i) \qquad (3)$$

curves. Researchers called them dot gain diagrams [8] or isocontours [9].

The dot gain diagrams (3) are popular measures of a conventional halftone printing system performance. Such measure is an inverse of the dot gain: more dot gain means less quality capabilities in the printing system. It is not a measure of image quality, but rather a process variable. Increasing of the dot gain by 20% does not mean degradation of the image quality by 20%. Dot gains for 133 lines/inch screens are different from those for 85 lines/inch even measured in the same conditions [8].

The property of tone rendering, expressed in a TRC, is not enough to describe a generalized imaging system. Tonal information alone can not create an image. It is not enough to know how white is the whitest and how black is the blackest. One needs to know how tones are varying in the space of picture. It is the spacial properties of the tonal variations on the paper that create an image. These facts were well known to Optics and Photo Science. The importance of one over another shifted in different times. Non linearity of the H&D curve was a restriction in quality of pictures initially. Research in emulsions and understanding the mechanisms of human perception of tonal information shifted the stress onto the size of grains and resolutions. The role of the spatial properties became dominant in photo quality. Except high powered laser beams, Optics remains in the domain of linear TRCs. Lord Rayleigh suggested the first assessment of image quality for an optical system. It was based only on spatial properties of images and soon became a text in handbooks [10].

The halftone images for a long time remained out of reach for Image Science. The presence of photo processing in a pre--scanner era of Graphic Arts included the non linearities and triggered the attention to the TRCs. It led to revelations of the dot gain, which by its meaning is rather a spatial than tonal property of a printing system. Further understanding of the problem allows one to identify *micro* spatial properties of a paper -- ink system. These are the causes for *macro* property of halftones to transfer tonal information.

Image Contrast and CTF

Following Image Science [11], we will use the next definition of the image contrast:

$$c = (d_b - d_w)/(d_b + d_w). \qquad (4)$$

Usage of the image contrast is justified because the human eye does not see absolute densities. Instead, it perceives the difference between inked and non covered areas. Defined by (4), the image contrast is always normalized. Its highest value is 1 and the lowest is 0.

The contrast is a function of a spatial frequency. To understand it, one can imagine a 50% line screen with the given frequency printed on a paper. The white spaces will be smaller than those with ink, in spite of their initial equality on a form. It is equivalent to an apparent increasing of the density of non covered paper. This will lead to decreasing the contrast defined by the equation (4). Measuring the reflective density D of the printed screen with a densitometer with the aperture, bigger than the screen period, the apparent paper density D_w can be calculated as

$$D_w = -\log_{10}[2\mathrm{pow}(-D) - \mathrm{pow}(-d_b)] \qquad (5)$$

in the frame of Murray - Davies model. This value D_w can be substituted into equation (4) instead of d_w. The resulted value will be the contrast c corresponding to the spatial frequency f, equal to the given screen frequency. The procedure, being repeated for all screen frequencies of interest, will create the Contrast Transfer Function defined in the domain of spatial frequencies f:

$$c = c(f) \; . \qquad (6)$$

The CTF defined in this way corresponds to a Modulation Transfer Function (MTF) used in Optics [10]. Actual MTF of the printing system can be obtained from the CTF (6). The procedure is the same as in derivations of a sinusoidal transform from a square wave input [11].

Engineers used integral properties of the MTF for generation of a merit function -- quality factor number. They found it responsible for the overall performance of an optical system. As we showed earlier [12], this approach can be expanded to include the CTF. We used it as a quality measure of the performance of a lithographic printing system.

However, for optical systems, the TRC is always a straight line (we are excluding the extreme case of high power laser beams). It is not surprising that the quality of such a system can be described by a spatial property -- an integral of its

MTF. Tone reproduction does not contribute to the overall quality in this case.

In case of a halftone system, the tonal properties become contributors to the quality. The TRC of halftones is *macro* non linear. The deviation of the TRC from the straight line is a measure of the dot gain. It is accepted as a conventional description of the system's quality.

Model

Object of our study is a halftone printing system. We will demonstrate the equivalency of the two approaches by predicting the TRC from CTF. Our assumption is that the CTF of the system is known. One can establish it using the procedure (4) - (6) in a sufficiently wide range of frequencies. We will use only circular dot halftones to illustrate our solution.

The idea of the illustration is in a selection of the appropriate square wave used to define the CTF. We will do it so the actual size of a halftone dot *R* (the tint value and the screen frequency are known) will coincide with the half period of the wave, as we show on Figure 3.

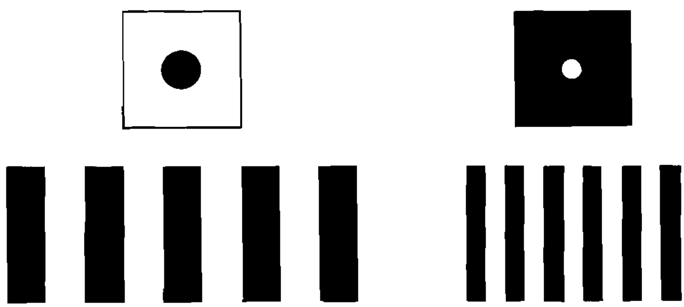

Figure 3. Selection of the square wave.

The actual size of the dot on paper can be calculated by involving the value of the known contrast. One can obtain it from the known CTF in the point

$$f = 1 / 2R . \qquad (7)$$

We use the Murray-Davies equation in these calculations together with simple geometrical considerations resulted from the structure of halftones. It is justifiable because the same equation has been used in the procedure (4) - (6) to define the CTF. Thus, the errors would be of a higher order of magnitude and we will neglect them. We relate to these considerations as the 1st order model.

We built a more rigorous model, named limiting, by using an equivalent micro optical system. Its MTF was calculated from the given CTF. The image of the known halfdot in the equivalent optical system was then calculated.

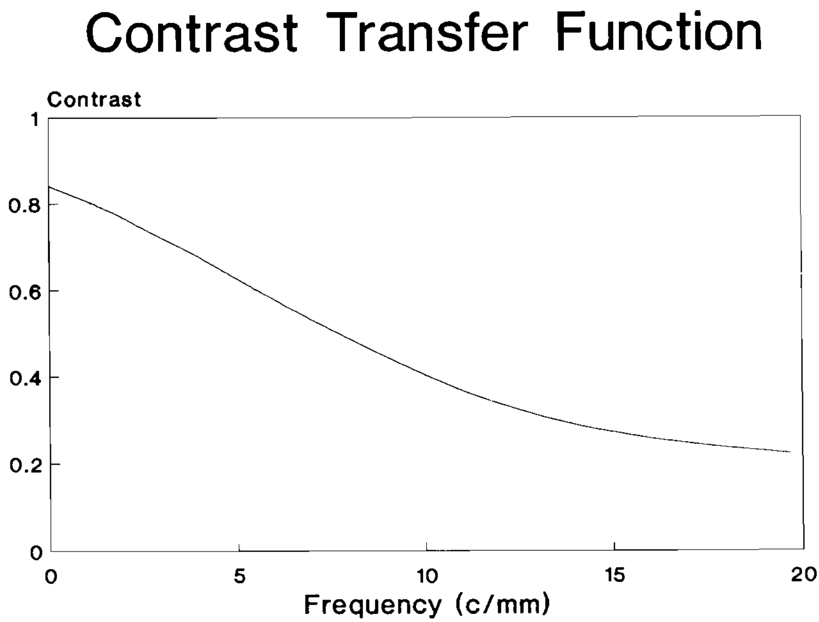

Figure 4.

Image intensity was averaged then over the halftone cell and used in definitions of resulting tints. Actual details of the calculations are highly complex and we will publish them elsewhere. The limiting model in principle is applicable to an arbitrary but defined shape of a halfdot.

Experiment

We verified the theory by printing the GURLAB™ Target together with a set of 133 LPI circle dot halftone tints. The set contained 9 tints with values 5, 10, 25, 40, 50, 60, 75, 90, and 95%. Every tint was a square with the size of 7/8 inch.

Printing was done on an 18" single color Heidelberg using the 80 lb Javelin coated stock of Champion. The inking keys were adjusted to give a consistent solid cover density at the level of d_b = 1.2 across the web.

We measured the CTF using the GURLAB™ System for Image Quality Measurements with the X-Rite 404 reflective densitometer. It had status T filters and 3.8 mm aperture. The results are plotted on Figure 4.

We used the same densitometer to acquire density values of the printed tints. The final value D_t of a tint density

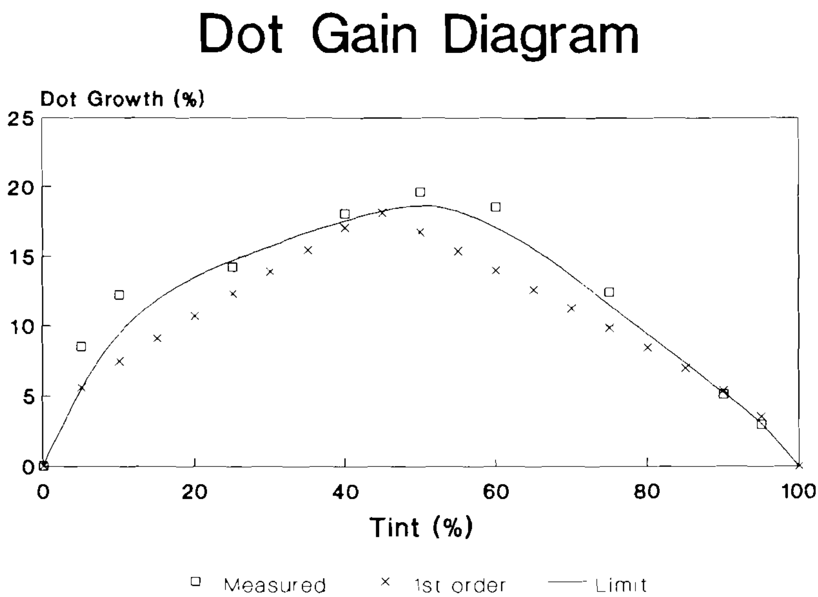

Figure 5.

substituted into equation (2) was a result of averaging over at least 32 randomly sampled measurements. The values of printed tints are presented on Figure 5. together with the line calculated from the 1st order model.

Dot gain diagram contains the comparison of the measured values, 1st order and limiting models.

Conclusions

Two approaches to the description of performance quality of a halftone system -- Tone Reproduction Curve and Contrast Transfer Function -- are equivalent.

Tone Reproduction Curves for arbitrary screen frequencies can be predicted from a known Contrast Transfer Function.

Acknowledgments

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