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Tone reproduction by some specific contact screens

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Abstract

A new and basic approach for the analysis of cell patterns of some specific contact screens and the reproduced halftone images is presented. Optimum parameters for high fidelity tone reproduction by screens of line, square, circular, and concentric ring cell patterns possessing optical transmittance linearly varying with position have been obtained. These parameters can be used for the design of contact screens, the selection of high-gamma films, and film exposure and development process to achieve optimum fidelity image reproduction. In addition, a comparison of the linear screen with screens of non-linear cell transmittance including the sinusoidal, exponential, and logarithmic screens has been made.

Introduction

In graphic arts and printing industry, the reproduction of a continuous tone photograph is achieved by the use of a screen to transform the original photograph into a binary or halftone negative (photograph) consisting of arrays of opaque dots with sizes varying according to the optical density of the original[1]. The halftone negatives are conventionally used for the making of printing plates.

The screens are classified into contact and non-contact types according to the way they are used during the exposure in making the halftone negative. Contact screens are placed in close contact with the emulsion side of the high contrast film. On the other hand, non-contact screens are placed at a distance from the high contrast film. For non-contact screens, the distance between the screen and film is determined by calculating the diffraction function of the aperture of the screen[2~4]. This distance is set to achieve the desired average value of the reproduced tone. For contact screens the optical transmittance of the screen cells (instead of the diffraction effect through the non-contact screens) determines tone reproduction. The scope of this paper is limited to contact screens only.

In general, the process of achieving "ideal" tone reproduction in printing is by no means simple. Contact screens with cells of various geometrical patterns have been made commercially available for obtaining printing dots of square, round, or elliptical shapes[5]. The shapes of these dots have an impact on the human visual perception of the reproduced image. For example, it seems that elliptical dots can give a more smooth transition in the middle tone range of an image than other dots. In addition, screens have been designed for making halftone positives from continuous tone negatives and also have been made in magenta color instead of gray. In the practical applications of these screens, a "masking" technique has been used to shorten the tone range of the original transparency for it in order to fit into the range that can be achieved by printing. Three exposures namely, "bump" (without screen), "main" (with screen and original image), and "flash" (with screen but no image) are recommended to bring out the highlight, middle tone, and shadow ranges of the original image. When the simple and direct halftone negative-making method could not satisfy the demand of the quality of the reproduction, then the more sophisticated indirect method and the extremely expensive electronic scanner method would have to be used[6]. In the viewpoint of the authors, most of the complications and difficulties in making the halftone negatives have originated from the fact that the screens are produced by empirical methods, and therefore, the optical transmittance of the screen cells is not yet optimized for tone reproduction. The additional steps such as "masking", "flash", and "bump" are adopted to compensate for the imperfection in screen design. Improvement in screen design will simplify the making of halftone negatives.

The precise design and fabrication of contact screens have lately become more important since the screen technique has been found useful in achieving various coherent and incoherent image processing functions[7~25]. Moreover, Bryngdahl[26] has shown pictorially that halftone screens of concentric-ring cell patterns can produce more details in case the original image is undersampled. He made a qualitative statement that this probably is because the dots produced by these screens have a higher circumference-to-area ratio. Pappu *et al*[27] have experimentally demonstrated that round halftone dots get distorted in undersampled images, whereas it is preserved to a great extent in sufficiently sampled images.

In order to improve the screen design, it is necessary to clearly and quantitatively define the functional dependence among the parameters that determine the relationship between the original image and the reproduced. The parameters include the gamma and threshold energy of the high contrast film, the optical transmittances of the input original image and the output image, and the optical transmittance as a function of the distance of the unit cell of the contact screen. Transmittance, instead of intensity, should be used since it is independent of the input light intensity. In the following section, we shall apply a simple and basic approach to treat this problem. There are many types of contact screens which possess cells with optical transmittance that varies either linearly or nonlinearly with distance. For reasons to be given, we shall present the results of our analysis of screens of unit cells with linear optical transmittance. We shall only limit ourselves to screens of line, square, round, and concentric-ring patterns.

Brief results on the first three cell patterns have been reported elsewhere[28,29]. The optimum parameters for high fidelity tone reproduction by screens of these patterns are reported. In addition, a comparison of the linear screens to those with nonlinear optical transmittances are made. This comparison is essential because most of the screens existing in the market have nonlinear transmittances. Guidelines to high fidelity tone reproduction by screens of linear cell transmittances will be deduced. The justification for choosing screens only with linear optical transmittance for our analysis will also be made.

Analysis

For simplicity, our analysis will be based on the following fundamental assumptions: (i) The transmittance of the unit cell of the screen is linear, (ii) the continuous tone original is sufficiently sampled by the screen so that the transmittance of the original over any one unit cell remains constant, (iii) the halftone copy is made on a

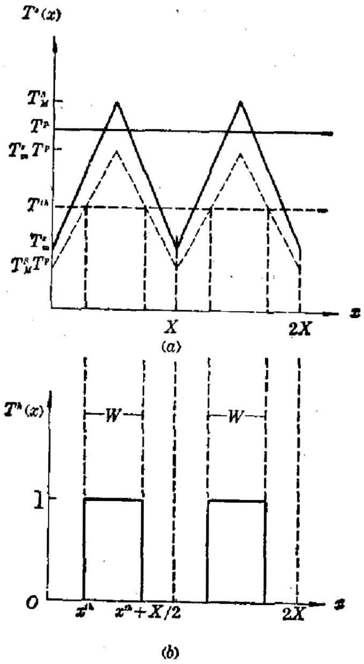

Fig. 1 Halftone process with screens of line cells

(*a*) Transmittance of two neighboring cells, the image, the threshold, and the screen in contact with the image;
(*b*) Transmittance of resulting halftone photograph

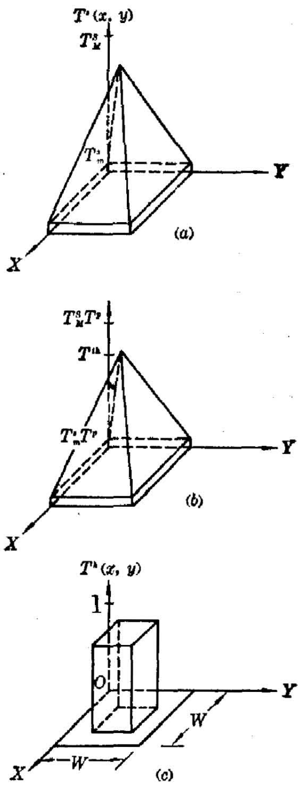

Fig. 2 Halftone process with screens of square cells

(*a*) Screen transmittance of one cell;
(*b*) Combined transmittance of the screen in contact with the image;
(*c*) Transmittance of the resultant halftone photograph

positive high contrast film* of infinite (or extremely high) gamma, and (iv) the scattering of light under the opaque area of the recording medium[30] is neglected.

The halftone processes with the use of screens of periodic line, square, circular and concentric-ring shaped cell patterns, are illustrated respectively in Figs. 1~4. The linear transmittance T^S, in both one-dimensional and two-dimensional screens are shown in part (a) of these figures, where T^S_M and T^S_m represent respectively the maximum and minimum screen transmittances. The screens have a period X along the x-axis for one-dimensional $(1-D)$ screens. For two-dimensional $(2-D)$ screens, the period is W along both the x-axis and the y-axis. Hence for the line screen, the transmittance can be written as,

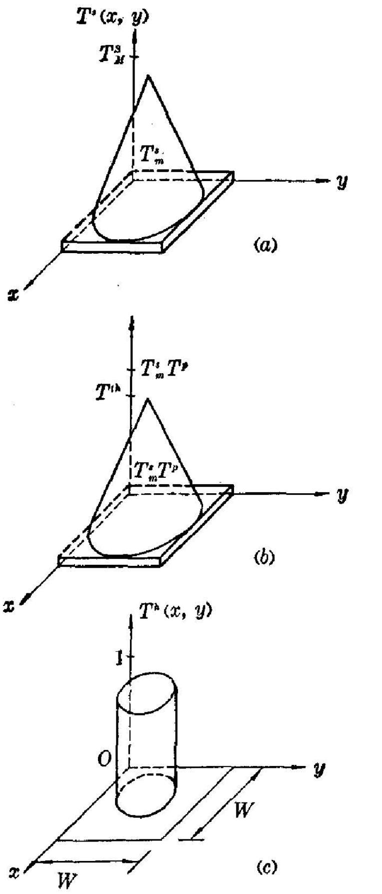

Fig. 3 Halftone process with screens of circular cells

(a) Screen transmittance of one cell;
(b) Combined transmittance of the screen in contact with the image;
(c) Transmittance of the resultant halftone photograph

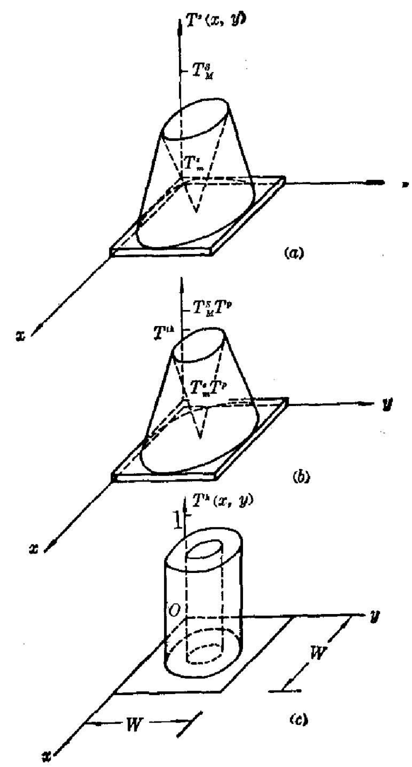

Fig. 4 Halftone process with screens of concentric-ring cells

(a) Screen transmittance of one cell;
(b) Combined transmittance of the screen in contact with the image;
(c) Transmittance of the resultant halftone photograph

* Most of the high-γ films are negative, we choose positive film for conceptual straight forwardness. One may also think it as an equivalence of a two high-γ negative film process.

$$T^S(x) = T^S(x+X), \tag{1}$$

and for the $2-D$ screens,

$$T^S(x, y) = T^S(x+W, y+W), \tag{2}$$

without loss of accuracy and again for simplicity, we further assume that for the screens of circular and concentric-ring cells, T^S_m is constant in the region of the cell bounded between the curve $x^2+y^2-(x+y)W+\frac{W^2}{4}=0$ and the straight lines $x=0$, $y=0$, $x=W$ and $y=W$. Without this assumption, dots produced by circular and ring-shaped ce l (and also for elliptical cells) get distorted at low threshold[27, 31] of exposure. The screens in contact with the original image of transmittance T^P has a combined transmittance T^ST^P with a maximum $T^S_MT^P$ and a minimum $T^S_mT^P$. In the photographic contact-printing process, when the transmittance T^ST^P exceeds or equals to the threshold transmittance T^{th}, as defined by I^{th}/I^{in} of the positive high-gamma film, the film will develop to have a transmittance of 1, in reality, the fog level; otherwise, 0. The notations I^{th} and I^{in} denote the threshold energy and the energy of the input illumination respectively.

The overall transmittance of a unit cell T^H, may be defined as the ratio of the transparent region (if the fog-level transmittance is taken as 1) to the total area of the unit cell. In the present case, while the original is assumed to be sufficiently sampled, T^H also represents the regional average transmittance of the halftone photograph. Based on the above definiton, T^H of screens of line (line), square (sq), circular (cir) and concentric-ring (ring) patterned cells are found respectively as functions of T^S_M, T^S_m, T^P and T^{th} as follows:

$$T^H_{\text{line}} = (T^S_MT^P - T^{th})/(T^P\Delta T^S), \tag{3}$$

$$T^H_{\text{sq}} = [(T^S_MT^P - T^{th})/(T^P\Delta T^S)]^2, \tag{4}$$

$$T^H_{\text{cir}} = \frac{\pi}{4}[(T^S_MT^P - T^{th})/(T^P\Delta T^S)]^2, \tag{5}$$

$$T^H_{\text{ring}} = \frac{\pi}{4}[(T^S_MT^P - T^{th})/(T^P\Delta T^S)], \tag{6}$$

where

$$\Delta T^S = T^S_M - T^S_m. \tag{7}$$

In addition it is noted that as T^P varies,

$$T^H = \begin{cases} 1, & T^P \geqslant T^{th}/T^S_m, \\ 0, & T^P \leqslant T^{th}/T^S_M. \end{cases} \tag{8}$$

Over any specific region, the difference between T^H and T^P namely T^H-T^P, may be used as a quantitative measure of the fidelity preserved in the contact screen process. Since T^P varies from 0 to 1 and T^H varies according to T^S_M, T^S_m and T^{th} consequently, T^H-T^P may have both positive and negative values over the range of T^P. For example, in case when a line screen is used, a plot of T^H-T^P versus T^P for $T^S_m=0$ and $T^S_M=1.0$

and T^{th} varying discretely from 0 to 1.0 is shown in Fig. 5, where the "+" and "−" signs indicate the positive or negative values of T^H-T^P over the range of T^P for $T^{th}=0.2$. The difference of T^H and T^P over the whole range of T^P may be defined as

$$\delta=\int_0^1 (T^H-T^P)\,dT^P. \tag{9}$$

With a given linearly transmitting screen of a known set of $\{T^S_M, T^S_m\}$, the value of T^{th} with which $\delta=0$ can be considered as the optimum threshold transmittance denoted by $T^{th}_{\rm opt}$ since the net difference of T^P and T^H for the whole range of T^P is minimized. The value of $T^{th}_{\rm opt}$ may be used for the selection of the high gamma film and the film development process for achieving optimum tone reproduction. Before $T^{th}_{\rm opt}$ is found for any of the screens considered, we must first evaluate the value of δ. The calculations of δ has to be divided into different ranges of T^{th} as follows:

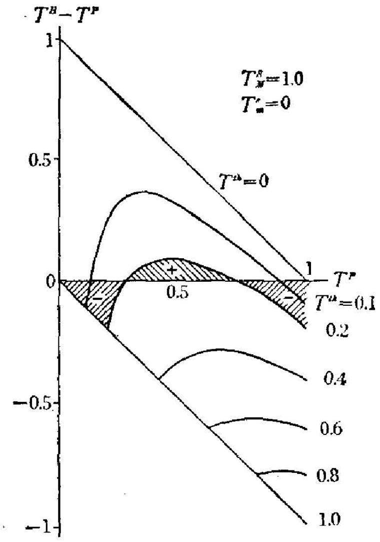

Fig. 5 T^H-T^P versus T^P for $T^S_m=0$, $T^S_M=1$, and T^{th} varying discretely from 0 to 1 in case of a screen of line cells of linear transmittance.

(i) $T^{th}=0$, for all the screens considered,

$$\delta=\int_0^1 (1-T^P)\,dT^P=\frac{1}{2}. \tag{10}$$

(ii) $0<T^{th}\leqslant T^S_m$

$$\delta=-\int_0^1 T^P dT^P+\int_{T^{th}/T^S_M}^{T^{th}/T^S_m} T^H dT^P+\int_{T^{th}/T^S_m}^1 dT^P. \tag{11}$$

After using Eqs. (3) ~ (6) with Eq. (11), one obtains

$$\delta_{\rm line}=\frac{1}{2}-(T^{th}/\Delta T^S)\ln(T^S_M/T^S_m), \tag{12}$$

$$\delta_{\rm sq}=\frac{1}{2}-T^{th}[(1/T^S_m)-\tau_1], \tag{13}$$

$$\delta_{\rm cir}=\frac{1}{2}-T^{th}\left[(1/T^S_m)-\frac{\pi}{4}\tau_1\right], \tag{14}$$

and

$$\delta_{\rm ring}=\frac{1}{2}-\frac{\pi}{4}T^{th}\left[\left\{\left(1-\frac{\pi}{4}\right)\Big/T^S_m\right\}+\{\ln(T^S_M/T^S_m)\}/\Delta T^S\right], \tag{15}$$

where,

$$\tau_1=\frac{T^S_M}{\Delta T^S T^S_m}-\frac{2T^S_M}{(\Delta T^S)^2}\ln\left(\frac{T^S_M}{T^S_m}\right)+\frac{1}{\Delta T^S}. \tag{16}$$

(iii) $T^S_m<T^{th}\leqslant T^S_M$

$$\delta=-\int_0^{T^{th}/T^S_M} T^P dT^P+\int_{T^{th}/T^S_M}^1 (T^H-T^P)\,dT^P, \tag{17}$$

which, combining with Eqs. (3) ~ (6), will yield

$$\delta_{\text{line}}=\frac{T_M^S}{\Delta T^S}-\frac{1}{2}-\left(\frac{T^{th}}{\Delta T^S}\right)\left[1+\ln\left(\frac{T_M^S}{T^{th}}\right)\right], \tag{18}$$

$$\delta_{\text{sq}}=-\frac{1}{2}-\tau_2, \tag{19}$$

$$\delta_{\text{cir}}=-\frac{1}{2}-\frac{\pi}{4}\tau_2, \tag{20}$$

and

$$\delta_{\text{ring}}=-\frac{1}{2}+\frac{\pi}{4}\left[T_M^S-T^{th}\left(1+\ln\frac{T_M^S}{T^{th}}\right)\right]\Big/\Delta T^S, \tag{21}$$

where

$$\tau_2=\frac{T_M^S T^{th}}{(\Delta T^S)^2}\left[1+2\ln\left(\frac{T_M^S}{T^{th}}\right)\right]-\left[(T_M^S)^2+(T^{th})^2\left(\frac{T^{th}}{T_M^S}-1\right)\right]\Big/(\Delta T^S)^2. \tag{22}$$

(iv) $T_M^S<T^{th}\leqslant 1$

$$\delta=-\int_0^1 T^P dT^P=-\frac{1}{2} \tag{23}$$

for all screen designs.

It can be seen that T_{opt}^{th} can then be determined for the line, square, circular and concentric-ring patterned screens from Eqs. (12) and (18), Eqs. (13) and (19), Eqs. (14) and (20) and Eqs. (15) and (21) respectively. It is easy to solve for T_{opt}^{th} in the range of $0<T^{th}<T_M^S$ by letting $\delta=0$, which leads to

$$T_{\text{opt,line}}^{th}=\Delta T^S/[2\ln(T_M^S/T_m^S)], \tag{24}$$

$$T_{\text{opt,sq}}^{th}=1\Big/\left[2\left(\frac{1}{T_m^S}-\tau_1\right)\right], \tag{25}$$

$$T_{\text{opt,cir}}^{th}=1\Big/\left[2\left(\frac{1}{T_m^S}-\frac{\pi}{4}\tau_1\right)\right], \tag{26}$$

and

$$T_{\text{opt,ring}}^{th}=\frac{2}{\pi}\Big/\left[\left\{\left(1-\frac{4}{\pi}\right)\Big/T_m^S\right\}+\Delta T^S\ln(T_M^S/T_m^S)\right]. \tag{27}$$

On the other hand, corresponding solutions for T^{th} in the range $T_m^S<T^{th}\leqslant T_M^S$ from Eqs. (18) ~ (21) are not straight forward. Numerical iteration and/or digital computer technique are required to determine the "approximate" values of T_{opt}^{th}.

After we let $\delta=0$ and find the corresponding $\{T_M^S, T_m^S, T_{\text{opt}}^{th}\}$, a natural question arises, i. e., which $(T_M^S, T_m^S, T_{\text{opt}}^{th})$ of the set will yield the minimum of the absolute value of T^H-T^P over the whole range of T^P? The question demands us to look for $(T_M^S, T_m^S, T_{\text{opt}}^{th})$ with which the minimum (denoted by $A_{\min}$) of

$$A=\int_0^1|T^H-T^P|\,dT^P \tag{28}$$

be reached. Through this secondary and final step of optimization, we can find the optimum values $(T_M^S, T_m^S, T_{\text{opt}}^{th})_{\text{opt}}$, from which the values of $(T_M^S, T_m^S)_{\text{opt}}$ may be used for thedesign of screens, and the value of $T_{\text{opt}}^{th}\,[(T_M^S, T_m^S)_{\text{opt}}]$ for the selection of the high-gamma film such that the highest fidelity tone reproduction can be achieved.

Evaluation of Eq. (28) first needs us to find T^P at which $T^H - T^P = 0$, where T^H are given by Eqs. (3) ~ (6). We have found that there are up to two solutions for T^P (denoted as T^{P1} and T^{P2}) for the line and concentric-ring patterned screens and up to three solutions (denoted as T^{Pa}, T^{Pb}, and T^{Pc}) for the square and circular-patterned screens, such that for $0 < T^{th}_{opt} \leqslant T^S_m$,

$$0 < \frac{T^{th}_{opt}}{T^S_M} \leqslant T^{P1} \leqslant T^{P2} \leqslant \frac{T^{th}_{opt}}{T^S_m} \leqslant 1, \tag{29}$$

$$0 < \frac{T^{th}_{opt}}{T^S_M} \leqslant T^{Pa} \leqslant T^{Pb} \leqslant T^{Pc} \leqslant \frac{T^{th}_{opt}}{T^S_m} \leqslant 1, \tag{30}$$

and for $T^S_m < T^{th}_{opt} \leqslant T^S_M$,

$$0 < \frac{T^{th}_{opt}}{T^S_M} \leqslant T^{P1} \leqslant T^{P2} \leqslant 1, \tag{31}$$

$$0 < \frac{T^{th}_{opt}}{T^S_M} \leqslant T^{Pa} \leqslant T^{Pb} \leqslant T^{Pc} \leqslant 1. \tag{32}$$

The details of the solutions are omitted to save space.

To illustrate the physical meaning of the calculated results, the minimum values of A are plotted versus T^S_m for $T^S_M = 0.912$ in Figure 6. From the Figure, it can be found that A_{min} equals 0.0862, at $T^{th}_{opt} = 0.2017$ and $T^S_m = 0.18$ for the square screen; 0.0766 at $T^{th}_{opt} = 0.1455$ and $T^S_m = 0.20$ for the circular screen; and 0.05797 at $T^{th}_{opt} = 0.1535$ and $T^S_m = 0.15$ for the concentric-ring screen. It is clear from Figure 6 that for all values of T^S_m, except for $T^S_m < 0.05$, A_{min} is consistently smaller for screens with cells of concentric-ring patterns. Selection of T^{th}_{opt} at the fixed T^S_m that makes A to be at the minimum should give the highest fidelity tone reproduction.

A Comparison of Contact Screens:

In the above analysis, we have confined our treatment to contact screens with cells of spatially linear optical transmittances. However, in practice, most contact screens are nonlinear. Since the transmittances of the unit cells vary from screen to screen, it is not possible to analyze all the screens. Nevertheless, it is important to compare the screens of linear and nonlinear cell transmittance. For simplicity, the comparison will be based on one-dimensional screens only. The nonlinear screens are represented by those with sinusoidal, exponential, and logarithmic cell transmittances described res pectively as follows:

Sinusoidal:

$$T^S(x) = \sin\frac{\pi x}{x}, \tag{33}$$

Exponential:

$$T^S(x) = \exp\left[9.21\left(\frac{x}{X} - 0.5\right)\right], \tag{34}$$

and Logarithmic:

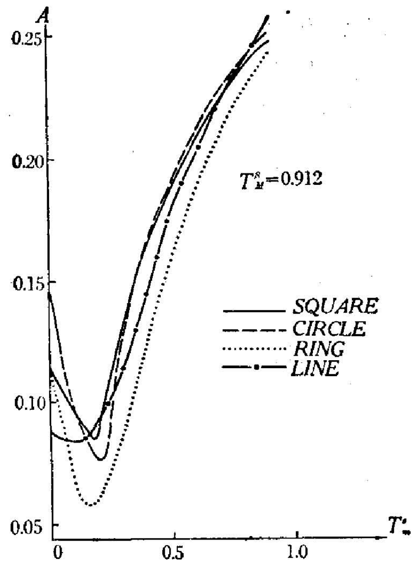

Fig. 6 Area A versus T^S_m for $T^S_M=0.912$ for screens of line square, circular, and concentric-ring cells.

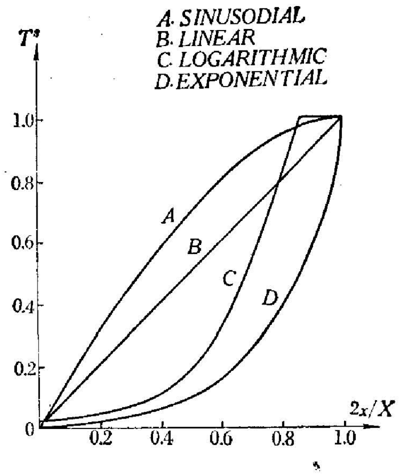

Fig. 7 Transmittances of sinusoidal, linear, logarithmic, and exponential cell patterns versus $2x/X$.

$$T^S(x)=\frac{0.02}{e^{4.6\left[\frac{2x}{X}-1\right]}}. \tag{35}$$

These transmittance functions together with the linear function are plotted versus $x\left(\text{for } 0\leqslant x\leqslant\frac{x}{2}\right)$ and shown in Figure 7, where X is the width of the unit cell. Most commercial screens have cell transmittance curves falling between the sinusoidal and exponential curves. In addition, the tone reproduction for these screens and the screen of linear transmittance, T^H (T^P), are plotted with T^{th} of the high contrast film as an adjustable parameter and are shown respectively in Figures 8~11. The dashed line in each of Figures 8~10 represents the ideal (or the most faithful) tone repro-duction curve. This curve coincides with the $T^S(x)$ curve in Figure 11. Comparing the tone reproduction curves in these figures show that $T^{th}\sim0.2$ for the sinusoidal screen; $T^{th}\sim0.05$ for the exponential screen; $0.05<T^{th}<0.1$ for the logarithmic screen; and $T^{th}\sim0.2$ for the linear screen will give the optimal reproduction. It is interesting to note, however, that none of the screens can give exact tone reproduction. This comparison offers a comprehensive insight into the various contact screens and justification for the choice of the linear screens in the analysis. Fabrication of any of these screens can be achieved by a method that has a patent pending[32]. The method is different from and much simplier than the computer-assisted microdensitometer screen generation method. The latter requires much time to generate a small piece of screen. In the use of the patent-pending method, large-format screens can be produced within a very short period of time.

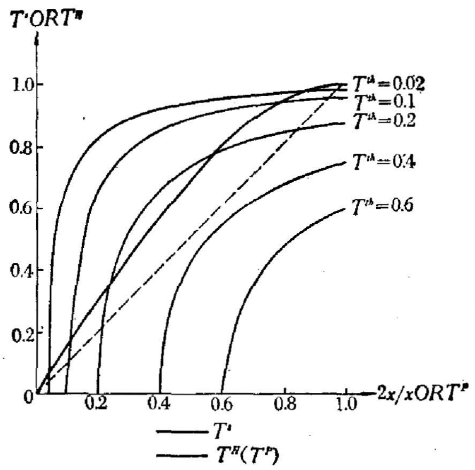

Fig. 8　T^S or T^H versus T^P as T^{th} varies discretely for the sinusoidal screens

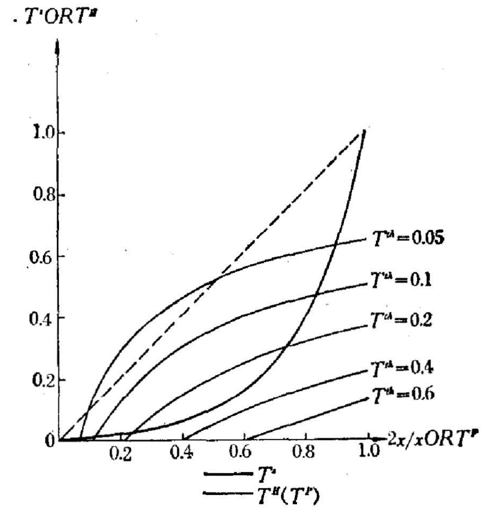

Fig. 9　T^S or T^H versus T^{tP} as T^{th} varies discretely for the exponential screens

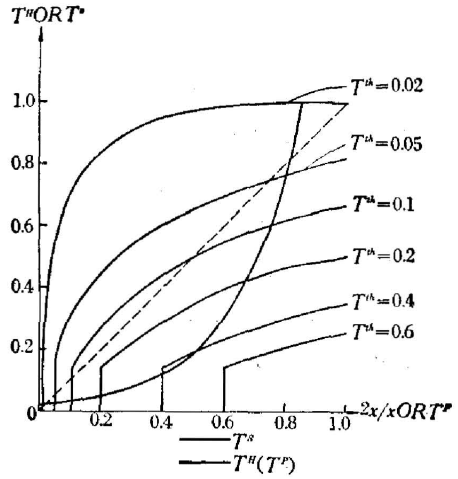

Fig. 10　T^S or T^H versus T^P as T^{th} varies discretely for the logarithmic screens

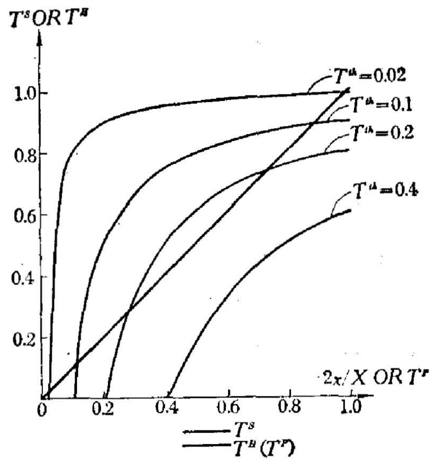

Fig. 11　T^S or T^H versus T^P as T^{th} varies discretely for the linear screens

Conclusion

We have presented a theoretical analysis of tone reproductions by halftone contact screens with cells of linear optical transmittances. We have shown that the regional average transmittance of the screen can be related to the transmittances of the original image, the threshold of the high-gamma film and the maximum and minimum transmittance of the screens. Special screen cell patterns which are analyzed include straight lines, square, circular, and concentric-rings. For each of these screens we have found that corresponding to each pair (T^S_M, T^S_m) there exists an optimum threshold transmittance T^{th}_{opt} such that the fidelity of the reproduced image reaches an optimum. If high fidelity image reproduction is desired through the linearly transmitting screens, this threshold transmittance can be used as a guideline for the selection of the high-gamma film, the exposure, and the film developing process. Furthermore, for all $\{T^S_M, T^S_m, T^{th}_{op}\}$ an additional optimization process has been applied and values of T^S_M, T^S_m, and T^{th}_{opt} have been found for these screens. When a screen is designed with these values of T^S_M and T^S_m and when the high-gamma film, exposure, and developing procedure are chosen to achieve a threshold transmittance of T^{th}_{opt}, the image reproduction should reach its highest fidelity. It is important to note that the analysis is limited in scope since only the transmittances of the halftone photograph and the original image are related. Other important practical problems, encountered especially in printing, including the faithfulnesses of image transfer between the halftone photograph and the printing plate, the purity of ink, the transfer of the image from the printing plate to paper or other recording media, the illumination of the final reproduced image, and human visual response of the reproduced are omitted in our analysis.

A comparison between the screens with linear cell transmittance to screens with nonlinear cell transmittance all in one dimension shows that the goal of the analysis has been reached.

Within the limited scope, it can be seen that the basic definition of T^H and the analytical approach adopted can also be applied in the determination of the selection of high contrast film, exposure, and development process for optimum fidelity reproduction once the transmittance profile of a given halftone screen is known. Such a profile can be easily measured by the use of a microdensitometer. Therefore the new method illustrated in this paper should have general image processing, printing, graphical arts, and pictorial transmission applications using existing halftone screens.

Acknowledgment

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对一些特定密着网屏作色调相减处理的方法

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提 要

本文提出了分析几种特殊的密着网屏网目模式及其所复制的半色调图象的一种基本方法，对于网目呈直线、正方形、圆以及同心圆等形状，并且它们的透过率随空间线性变化的网屏，我们得到了能最逼真地复制图象色调的一组最佳参数。根据这组参数，我们可以设计密着网屏，选择高反差胶片及其曝光和冲洗条件，从而达到最逼真地复制图象之目的。此外，考虑到其它实用因素，我们也将线性网屏与包括正弦形、指数形、对数形等非线性透过率网目的网屏进行了比较。

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