C. INTRODUCTION TO THE MODULATION TRANSFER FUNCTION

Electron optical systems have been evaluated in various ways. Usually some technique is used to plot electron trajectories and establish the paraxial image. Sometimes the image surface and aberrations are considered and estimates of resolving power are made. Until the advent of high speed electronic computers the accuracy of these results was quite limited.

In the past, the practical way of determining the resolving power of an image tube was a visual subjective measurement of the limiting resolution that could be observed by the eye. A resolution pattern having a series of alternating black and white bars is focused on the photocathode by a projector. The photocathode emits electrons in a density pattern corresponding to the white bars and these electrons are accelerated and focused on the phosphor screen by the electron lens. The resolution pattern is then observed by the eye, usually through a microscope. The eye can perceive a difference in contrast of about three percent. The limiting resolution of the image tube then, represents the situation where the contrast between the smallest black bar and white bar pair in the series which can be distinguished is about three percent. If the

NOTE: THIS EXCERP TAKEN FROM RCA REPORT No. LCIT-71-TR-001 THE MODULATION TRANSFER FUNCTION APPLIED TO ELECTROSTATIC ELECTRON OPTICAL SYSTEMS OF IMAGE TUBES BY LAWRENCE A. EZARD. RCA LIBRARY transmittance of the black bars is not zero then the resolution observed by the eye represents a measure of resolving power at that particular image contrast level.

In recent years the modulation transfer function has become the standard way to specify the imaging properties of an optical component. Its principal attributes (for linear, spatially invariant optical systems) are as follows:

(1) No matter how badly a lens images an incoherently illuminated sinusoidal pattern, the image always remains sinusoidal and at most, only the amplitude (or modulation) of the sine wave and the phase are altered [25]. This is not true for other more general types of patterns. For example the edges of a square wave pattern (bars) will become rounded when imaged through an optical system, thus distorting the shape of the original pattern.

(2) The MTF is a measure of the relative contrast of the image for all spatial frequencies.

(3) Fourier analysis demonstrates that any general type of one-dimensional pattern can be considered to be composed of a number of sinusoidal patterns having the proper amplitude and frequency. Thus the relative contrast for any kind of pattern

could be calculated starting with the MTF.

(4) For optical systems consisting of a chain of components, the MTF of the complete system is simply the product of the MTF's of the components.

To gain perspective it is worthwhile to discuss the MTF more fully. A method for measuring the MTF is sketched in Figure 3. The test object, TO, can be a film having a transmittance which is sinusoidal with various spatial frequencies. The various spatial frequencies are placed successively in the illuminated object space of the lens, L, and the images of these test objects are scanned by the slit, S, by moving the test object. The light passing through the slit is measured by the phototube, P, and recorded on the recorder, R. The lens acts as a spatial frequency filter and reduces the amplitude of the various spatial frequencies in the test object.

In Figure 3, it is possible to interchange the positions of the sinusoidal test object and the slit. In this case then, for an infinitesimally small slit, the image formed by the lens would represent a line spread function. This LSF is focused on the sinusoidal pattern, the signal is detected by the phototube and amplified, and finally the signal is displayed on the recorder.

To examine the measurement of Figure 3 in more detail, consider that the sinusoidal pattern can be written as $f(x) = b_o + b_1 \cos 2\pi fx$ where f is the spatial frequency in cycles per millimeter (see Figure 4). The recorder, R, displays a sinusoidal pattern with a peak white signal level, B_W, and a black signal B_B. The MTF is defined in terms of contrast as the ratio $(B_W - B_B)/(B_W + B_B)$ given as a function of frequency. But $B_W = b_o + b_1$ and $B_B = b_o - b_1$. Substitution of these values of B_W and B_B into the equation leads to the ratio b_1/b_o as a function of frequency.

A consideration of the electronic analog to Figure 3 is useful (see Figure 5). A signal generator (test object) supplies various sinusoidal frequencies to the linear, time invariant, network (lens). The frequency analyzer (slit and phototube) measures the amplitude of the output of the linear network and the recorder displays the information. Continuing the analogy we recall from communication theory that the unit impulse response of a linear network characterizes the network. Turning to Figure 6 we consider the output g(t) from a linear network characterized by its impulse response, h(t), with an input, f(t). Now g(t) is the convolution of f(t) and h(t).

(1.6) $$g(t) = \int_{-\infty}^{\infty} f(t)\, h(t - \tau)\, d\tau$$

Using Fourier transforms we can express the relationship between the Fourier transforms of the output, G(s),and the Fourier transforms of the input signal F(s) and the network H(s) in the form

(1.7) $$G(s) = F(s)\, H(s)$$

If the input signal is the unit impulse whose Fourier transform is unity then G(s) is equal to H(s).

Returning to the light optical case we will consider a point spread function (see Figure 7). The point spread function is simply the image of a point source of light. The amplitude of the function represents light intensity.

The point spread function, PSF, should be recognized as the basic building block of an optical image since any image can be considered to be made up of an infinite number of point spread functions having the appropriate intensity. It is worthwhile to consider the relationship between the point spread function and the line spread function, LSF. While the PSF is the image of a point, the LSF represents the image of a line (see Figure 7b). In both cases the amplitude of the function represents light intensity. The PSF is a function of two dimensions while the LSF is a function of only one dimension.

In practical laboratory measurements the LSF is often preferred over the PSF to permit the collection of sufficient light to operate the phototube above background noise. By considering the point object to by infinitesimally small, its spectrum (or Fourier transform) contains all frequencies at equal amplitudes as shown in Figure 8. The image will be spread out as shown and its Fourier transform yields the MTF of the lens under test.

We now turn to the electron optical system of an image tube. We can consider electrons with various angular and energy distributions to leave a point on the photocathode (see Figure 9). The electrons arriving at the image surface will form an image point spread function whose amplitude represents the density of electrons in the image. The input is a point, or two-dimensional delta function, whose spectrum contains all frequencies at unit amplitude. The normalized Fourier transform of the image PSF will yield the MTF of the electron optical system of the image tube. The image aberrations will appear in the PSF and will result in reduced values of the MTF as a function of spatial frequency.

IV. CONCLUSIONS

The conclusions of this study can be summarized as follows.

1. The experimental measurements of a proximity focus image tube verify the theoretical relation that for a fixed value of MTF the spatial frequency is inversely proportional to the square root of the initial electron emission energy and directly proportional to the square root of the applied potential.

2. A technique was developed to estimate the effective electron emission energy by comparing MTF measurements in a proximity focus image tube with the theoretical MTF response.

3. The measurements indicate that the effective electron emission energies for the multialkali photocathode are lower than expected for incident visible light in the wavelength range of 400 to 800 nm. For incident photon energies from 1.45 to 2.48 eV the effective electron emission energies ranged from only 0.06 to 0.163 eV. In addition, the effective electron emission energies do not increase linearly with increasing incident photon energy. This information is important for practical reasons. If the electron emission energy increased linearly with an

increase in incident photon energy then the variation of resolution of the image tube would be much greater as the incident radiation is changed from red light to blue light. For white light incident on the photocathode, the image resolution would be lower than that actually observed.

4. A novel technique was developed and demonstrated to measure the MTF of an image tube by inserting an analyzing slit inside the image tube at the image plane, adjacent to the phosphor screen. Using this technique the MTF of the phosphor screen and the MTF of the electron lens of the image tube can be evaluated sequentially in the same tube. Moreover, the phosphor screen does not degrade the MTF measurement of the electron lens, since it acts only as an energy transducer to change electron energy to light.

5. The experimental measurements of the MTF of the electron lens of an image inverter tube were found to agree with theoretical models which predict that for a fixed value of MTF the spatial frequency varies inversely with the initial electron emission energy and directly with the electric field at the photocathode. This is important information since it

provides a method to predict the variation of MTF response if, for example, the potential on the image tube is varied to control the gain of the tube. In many applications, variable gain is achieved by controlling the voltage across the image tube.

6. The MTF response at low and intermediate spatial frequencies is often more important than the response at higher spatial frequencies since the useful spatial frequency range of many complete optical systems is less than 50 cycles/mm. The calculations of MTF response using the theoretical equation for the image aberration indicates that for low and intermediate spatial frequencies there is an optimum position to locate the image plane (or phosphor screen) to maximize the MTF. Moreover, the optimum position to locate the image plane varies with operating voltage and electron emission energy. Therefore, if the gain of an image tube is controlled by varying the potential applied to the tube, this effect must be considered.

7. The study of the electron lens of the RCA C21135 image tube using the RCA electron optics program demonstrated that the computer program can be precise enough to calculate the MTF of an image tube. Previously, the only recourse was to measure the MTF

response with operating tube models. The study shows that the program can calculate electron paths which are accurate to within about 0.1 mesh block at the image plane. This represented about three microns for the tube under study.

8. The experimental measurements of MTF made during the course of this study and the comparison with the theoretical models represents an advancement in the knowledge of the electron optics of image tubes. Although the theory for the image aberrations was well developed, the application of the theory to calculate the MTF and its comparison with experiment was an uncompleted task.

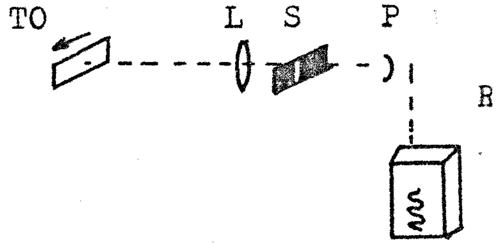

Figure 3 Schematic of apparatus for measuring MTF of a lens. TO is the sinusoidal test object, L is the lens being tested, S is a scanning slit, P is a phototube and R is a recorder.

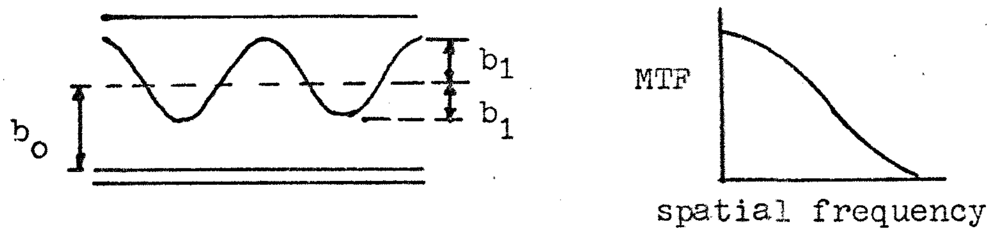

Figure 4 a) Sketch of a sinusoidal test object having a mean transmittance b_o and amplitude of transmittance variation b_1. b) MTF response versus spatial frequency.

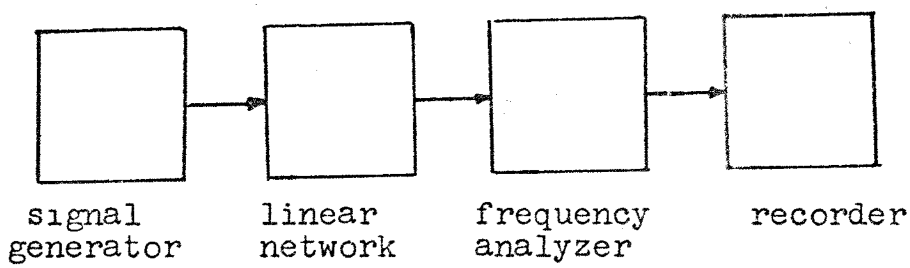

Figure 5 Electronic analog of Figure 3.

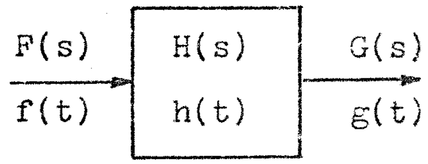

Figure 6 Linear network with input f(t) and output g(t) whose impulse response is h(t). The corresponding Fourier transforms are F(s), G(s), and H(s).

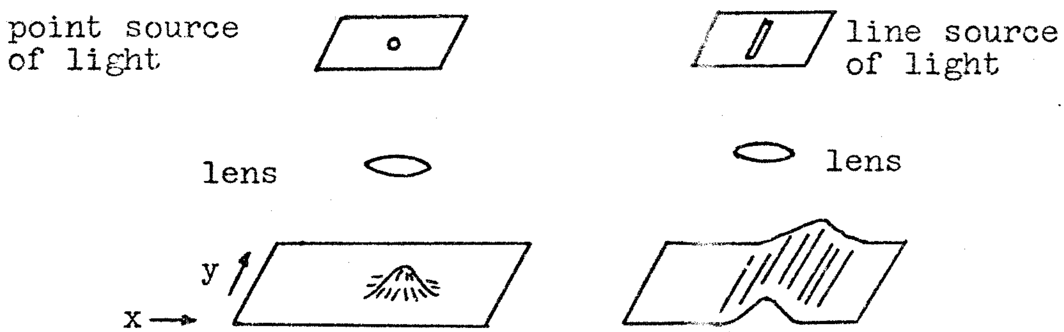

Figure 7 a) A method of forming and scanning a point spread function, b) a line spread function.
The amplitudes of the spread functions are depicted as elevations.

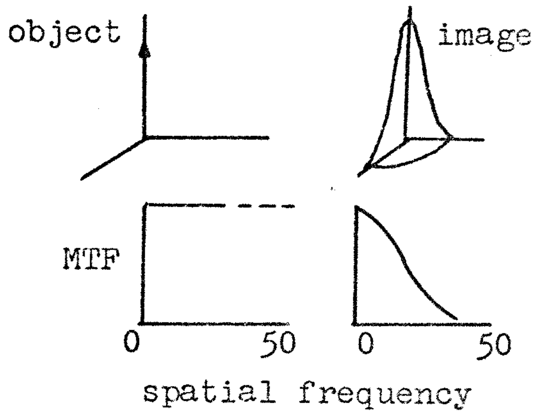

Figure 8 Point object and its image (above) and the corresponding modulation transfer functions (below).