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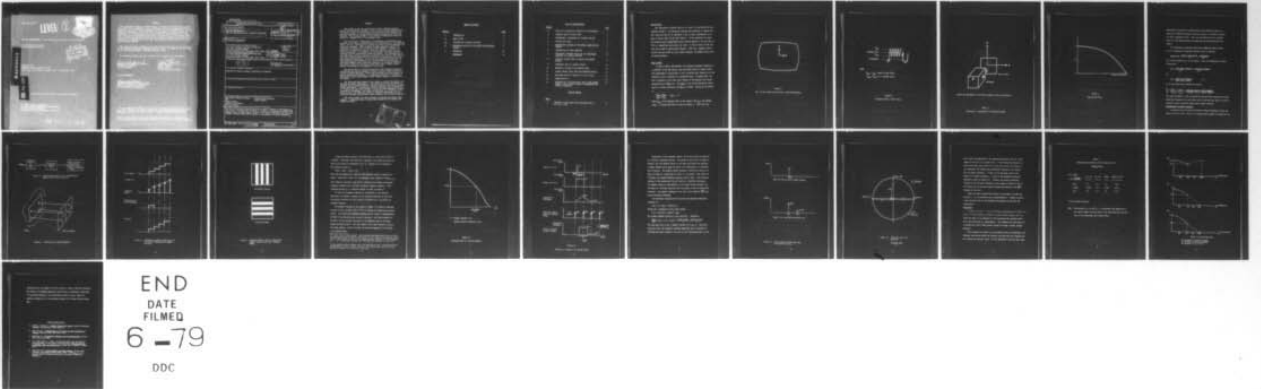
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DISPLAY MEASUREMENTS --- Can MTF Analysis Be Used on Matrix Displays?

System Technology Branch
System Avionics Division

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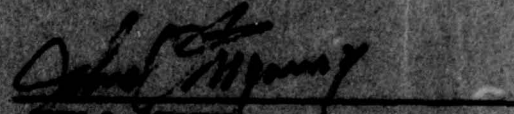
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Introduction

MTF (modulation transfer function) is useful in specifying the performance of CRT's. As new matrix displays are developed to replace the CRT, they will have to be evaluated to see if their performance is as good or better than the CRT they replace. If the evaluation of these new displays were accomplished using a method similar to the one used on CRT's, a comparison could easily be drawn. It may be that the MTF concept can be used on matrix-type displays. This report examines theoretically the use of MTF on one of these displays, the Hughes Liquid Crystal Matrix Display.

What is MTF?

As used in CRT's, MTF measures the frequency response (response to a sinewave) of the CRT system, from electronic input to visual output. This measurement is restricted to the X direction only (Figure 1) as the response in the Y direction is considered fixed. To measure MTF, one adds a sinewave to the video input (Figure 2) and measures the output photometrically (Figure 3). The ratio of the output modulation (photometric) to input modulation (voltage) is formed. Modulation is defined as

$$\frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}} \quad S_{\min} \geq 0,$$

where S_{\max} is the maximum value of the sinusoid and S_{\min} the minimum value. A typical MTF curve is shown in Figure 4. This curve was

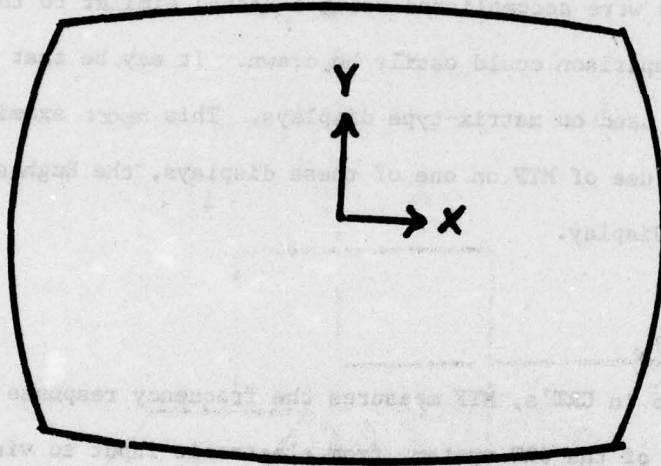
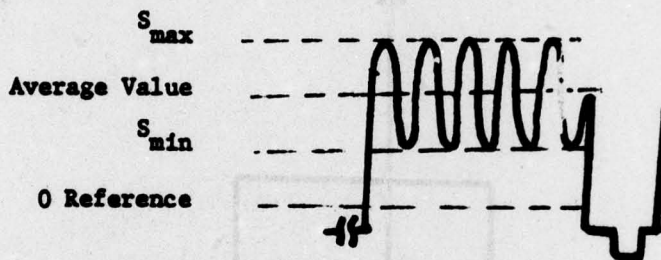


Figure 1.

Face of CRT Indicating Direction of MTF Measurements.



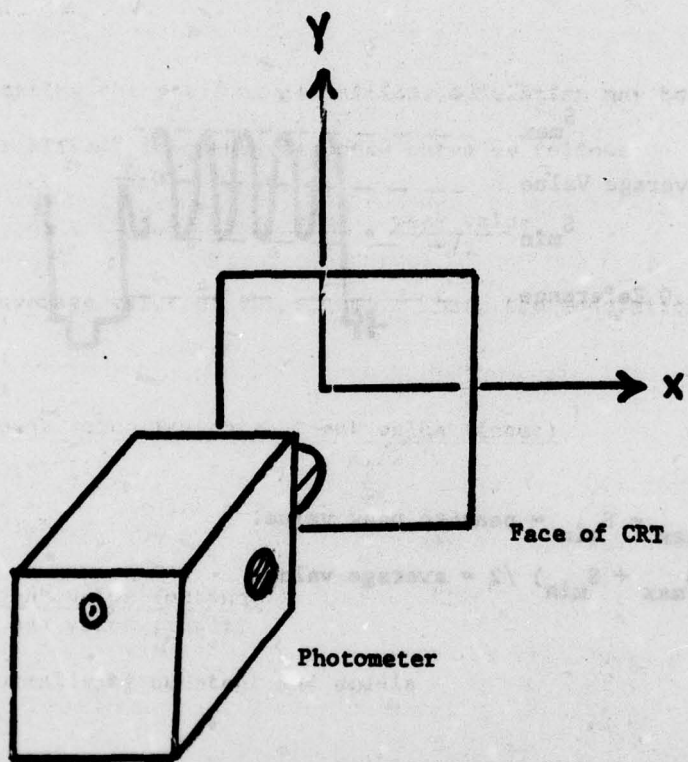
NOTE:

$$S_{\max} - S_{\min} = \text{peak to peak value.}$$

$$(S_{\max} + S_{\min}) / 2 = \text{average value.}$$

Figure 2.

Sinewave Added to Video Input.



Either the photometer or the CRT is moved in the $\pm x$ direction.

Figure 3.
Photometric measurements for Finding the MTF.

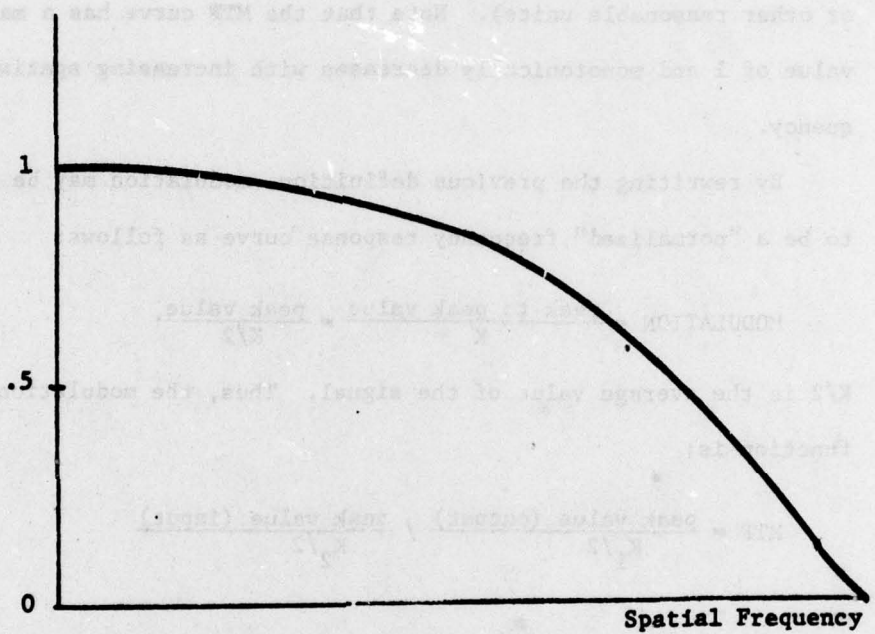


Figure 4.

Typical MTF Curve.

generated by plotting the dimensionless ratio described above as a function of spatial frequency (cycles per inch, or cycles per degree, or other reasonable units). Note that the MTF curve has a maximum value of 1 and monotonically decreases with increasing spatial frequency.

By rewriting the previous definition, modulation may be shown to be a "normalized" frequency response curve as follows:

$$\text{MODULATION} = \frac{\text{peak to peak value}}{K} = \frac{\text{peak value}}{K/2}$$

$K/2$ is the average value of the signal. Thus, the modulation transfer function is:

$$\text{MTF} = \frac{\text{peak value (output)}}{K_1/2} / \frac{\text{peak value (input)}}{K_2/2}$$

or

$$\text{MTF} = \frac{\text{peak value (output)}}{\text{peak value (input)}} \cdot K_3$$

K_3 is the normalizing constant and equals

$$\frac{K_2}{K_1} = \frac{(S_{\max} + S_{\min})}{(S'_{\max} + S'_{\min})} = \frac{(\text{average value of input signal})}{(\text{average value of output signal})}$$

Note that the MTF of a CRT is limited by the CRT drive electronics (video amplifier) bandwidth and the finite size of the CRT spot which is usually thought to have a gaussian shaped point spread function.

Applying MTF to Matrix Displays

It appears as if MTF may be measured on matrix displays in much the same way as for a CRT. That is, a sinewave input signal is formed and the

output measured photometrically. Since the matrix display is made up of discrete elements, however, the measurements would only be made until the spatial frequency was equal to 1/2 the maximum number of elements/display dimension (horizontal or vertical). The above frequency limit indicates that measurements should be made in both horizontal and vertical dimensions. This depends on the method of driving the display, but, in general, it is true.

In a matrix display, the input is sampled to give the discrete output. This sampling process creates frequencies which were not present in the input signal. These frequencies are predictable for any given sinusoidal frequency input and may be removed by low pass filtering the measured display output. If the matrix display is used to display a sine-wave equal in frequency to one half the number of display elements (actually slightly lower), then an ideal low pass filter would be used.

Apparently, as used for matrix displays, MTF refers to the maximum recoverable sinewave modulation after suitable filtering. That is, knowing the input signal modulation, one may multiply by the matrix display system MTF to find the maximum recoverable sinewave modulation that would be available in the measured output after filtering.

In this sense, MTF is useful. In fact, for displays of sufficiently high density, the human visual system performs this filtering operation and removes the sidebands generated by the sampling process. This gives the display a continuous non-matrix appearance.

In any sampled system, one must give consideration to the input signal spectrum. If the input signal is not sufficiently band-limited, aliasing problems occur and must be considered.

Estimating the MTF of the Hughes Liquid Crystal Matrix Display

An analytical estimate of the shape of the MTF curve for the Hughes' display can be found using a linear systems approach. Figure 5 shows the system. A hypothetical 1000 X 1000 element one inch square display is assumed. To analyze the response of the matrix display, imagine a perfect matrix where the output of any one cell is equal to the sampled portion of the picture input times a constant and is uniform across the cell, as in Figure 6. If we were to scan across this matrix photometrically, the output might be as shown in Figure 7(a). In Figure 7(b), it is shown how a signal of this form might be generated. Thus, Figure 7 shows that a signal generated by a sample and hold process is identical to the measured matrix display output. The response to a sine wave of such a system is well known and is of a $\frac{\sin x}{x}$ form. Reference [1] explains this fully. Realizing that the display itself gives a $\sin x/x$ or sample and hold system response, an estimate of the MTF of the system display, including the initial sample and hold electronics and the drain line electrical response, can be made. Two display outputs will be analyzed, one a vertical sine wave pattern, the other a horizontal sine wave pattern, both of varying spatial frequency. These patterns are illustrated in Figure 8.

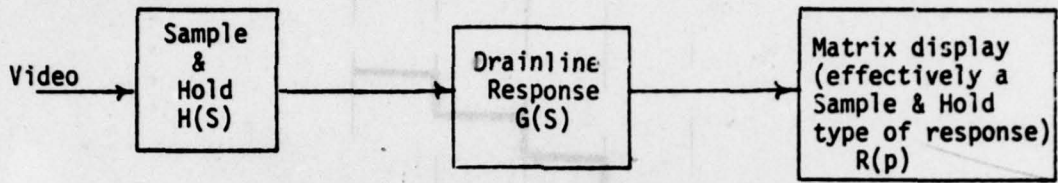


Figure 5. System Block Diagram of the Hypothetical Hughes Liquid-Crystal Display

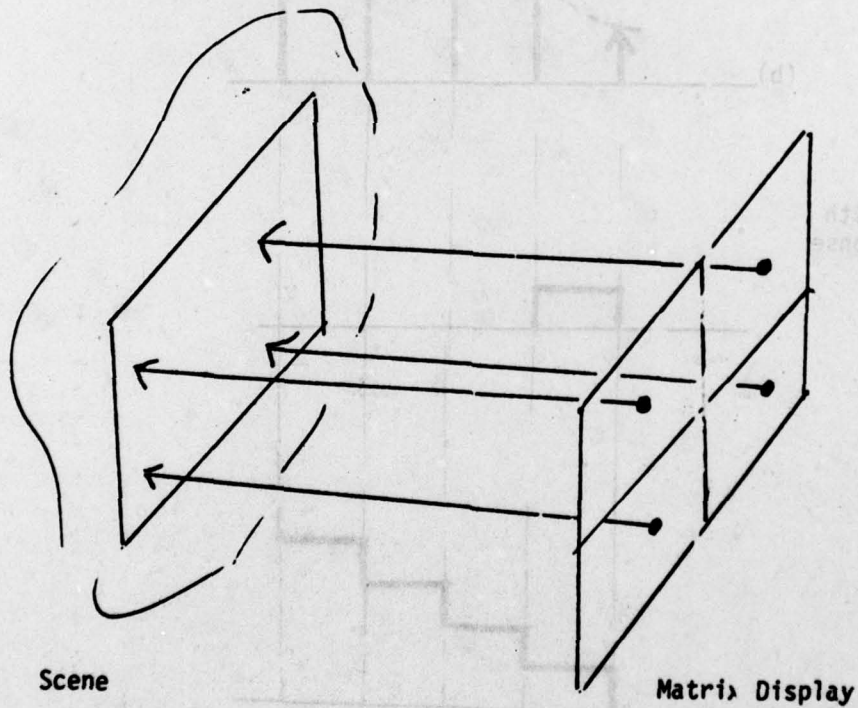


Figure 6. Illustration of Ideal Sampling

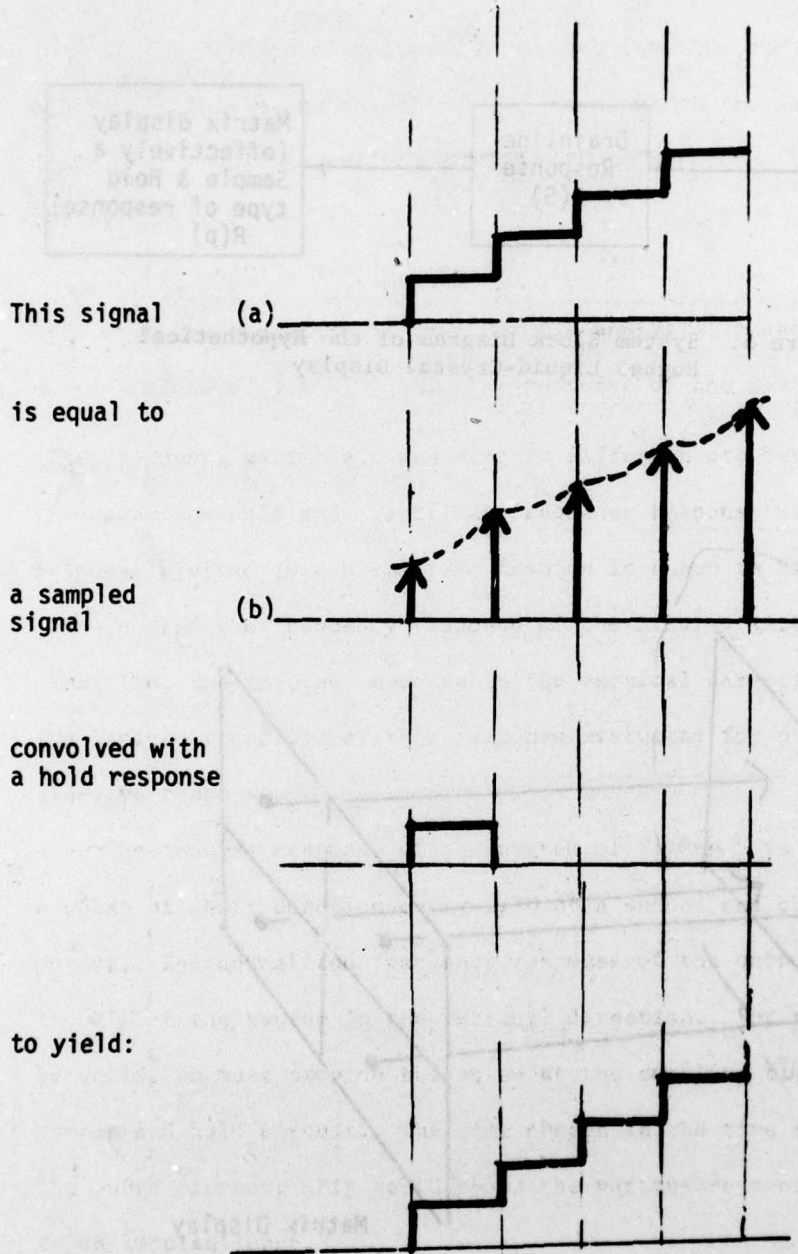
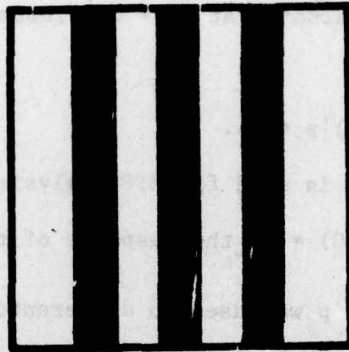
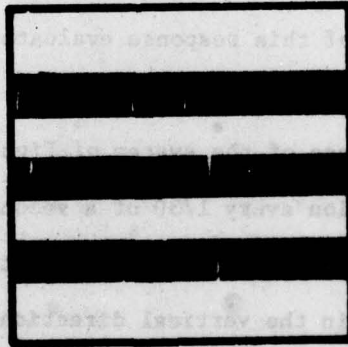


Figure 7. Photometric Response Signal and its Equivalent Generated by a Sample and Hold



Horizontal Pattern



Vertical Pattern

Figure 8. Sinewave Patterns used to Analyze the Hughes' Display (only one frequency shown)

In the horizontal pattern, the video input to each drain line¹ is a constant.² This means the electrical response of the sample and hold and drain line should be evaluated at $j\omega = 0$. Therefore, the response of the system is given by

$$|H(0) \cdot G(0) \cdot R(p)|_{p = j\lambda}$$

Note only the magnitude is used for MTF analysis; phase is usually ignored. Since $H(0) = G(0) = 1$, the response of the system is $|R(p)|_{p = j\lambda}$.

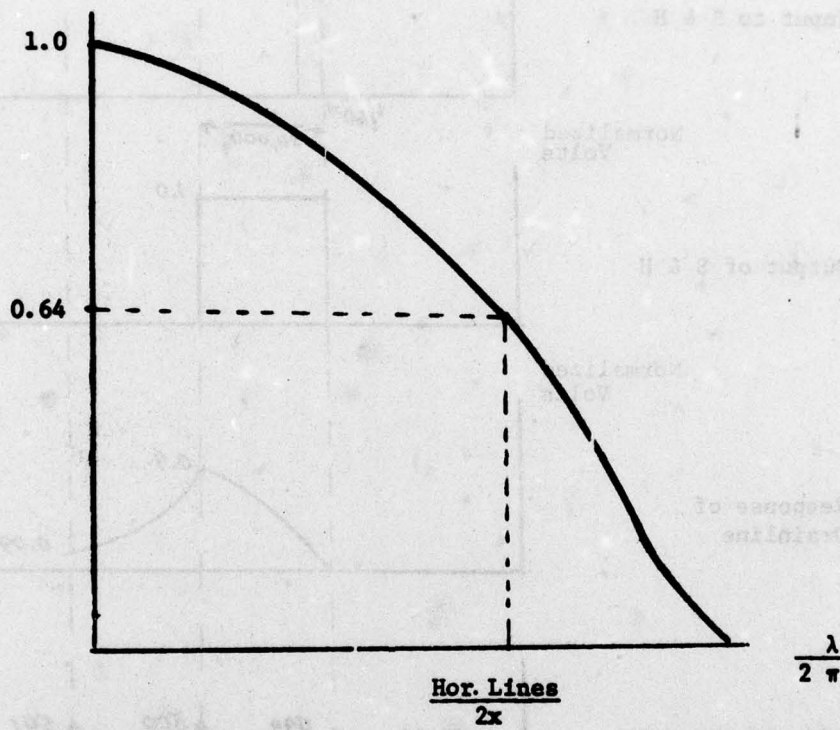
(The frequency variable p was used to differentiate between the spatial frequency variable and electrical frequency response variable.) This response plotted in a normalized fashion is shown in Figure 9.

To find the frequency response of the display in the vertical direction, the impulse response in the vertical direction is found and the Laplace transform of this response evaluated for $p = j\lambda$ gives the sinewave response.

The impulse response of the system of Figure 5 is found by applying a pulse of short duration every 1/30 of a second and observing the visual output. The normalized frequency response of the output is approximately the MTF of the system in the vertical direction. For this procedure to be valid, we must provide the pulse at the sampling time of the input sample and hold circuit. The time chosen is the time required to excite the 500th element. Figure 10 shows the various responses of the system to an impulse input.

¹The drain lines in the Hughes' liquid crystal displays used by the Air Force are essentially distributed RC transmission lines. These lines provide a path for the video signal to each of the sample and hold circuits at each elemental cell. It is this stored voltage that controls the luminance of each cell.

²In the general matrix display case, this may not be true. Analysis would be accomplished by using a method similar to the method used here to find the frequency response in the vertical direction.



x = inches, degrees, etc.

typical spacial frequency units.

Figure 9.

Horizontal MTF of a Matrix Display.

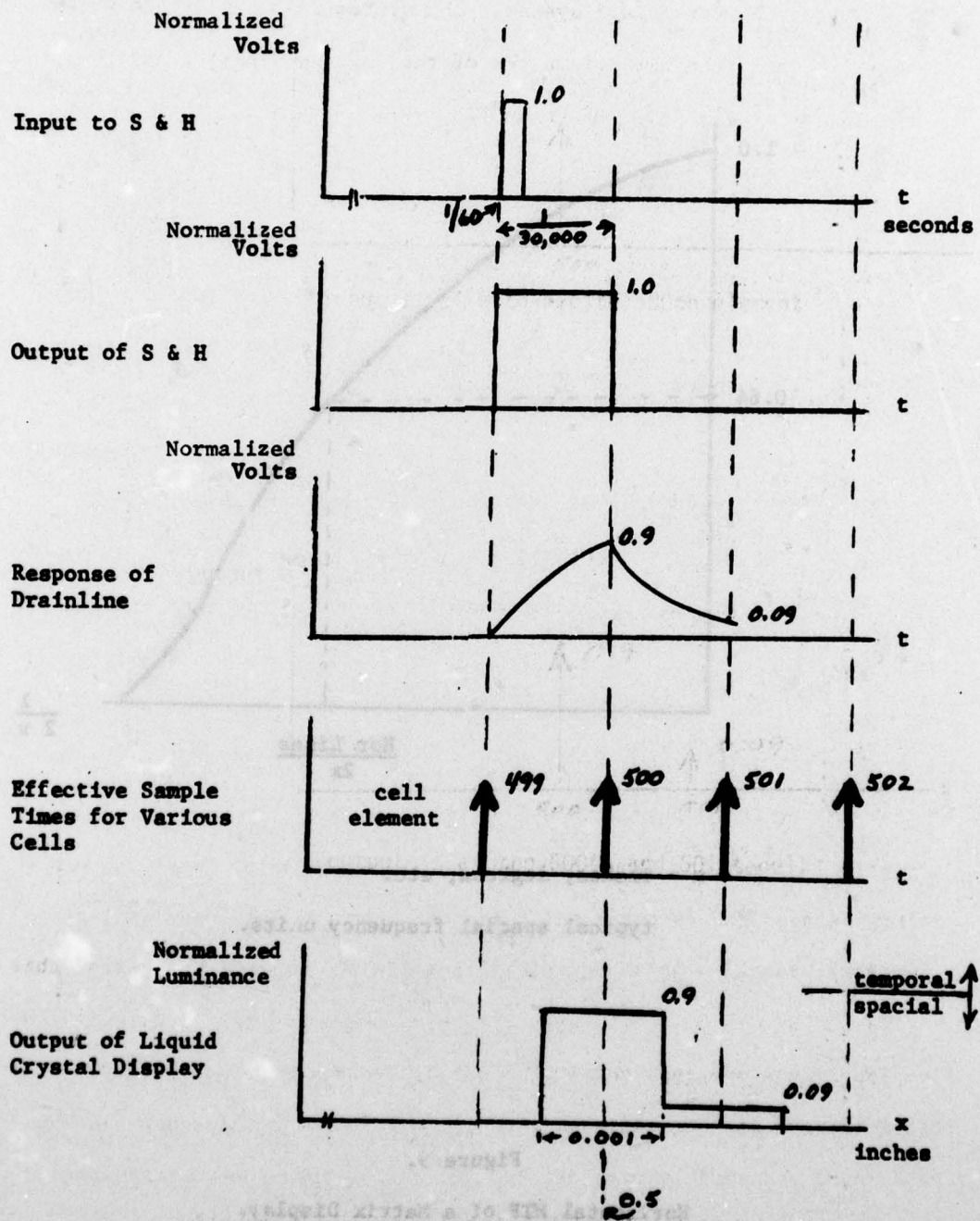


Figure 10.

Response of System to an Impulse Input.

Inspection of this response reveals it may more easily be analyzed as a discrete time/space system. The system is still that of Figure 5; however, only the sampled values of the input and output are observed. A single sampled input shown in Figure 10 is equivalent to a Kronecker delta function. The sampled system response to this delta function is shown in Figure 11 along with the input to the system. From these two waveforms, the system difference equation may be found. The frequency response of the system can then be found by z transform techniques. The sampled output is then applied to the liquid crystal display cell (by means of a holding capacitor) and the output is now in analog form spatially. The spatial response of the cell is the familiar $\frac{\sin x}{x}$ response previously discussed.

The difference equation which describes the discrete-time/space response is:

$$y(k) = 0.9 x(k) + 0.09 x(k-1).$$

Taking the z transform of both sides yields:

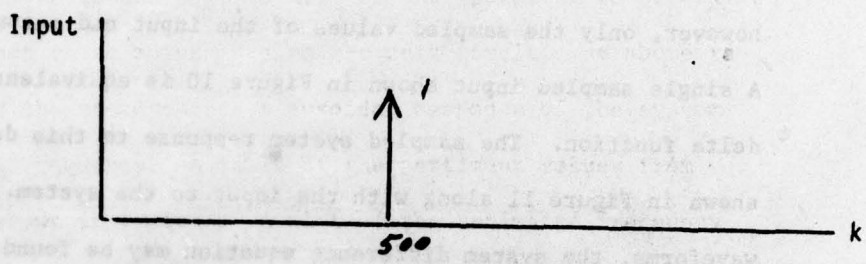
$$y(z) = 0.9 x(z) + 0.09 z^{-1} x(z).$$

The system transfer function is then $y(z)/x(z)$. Therefore,

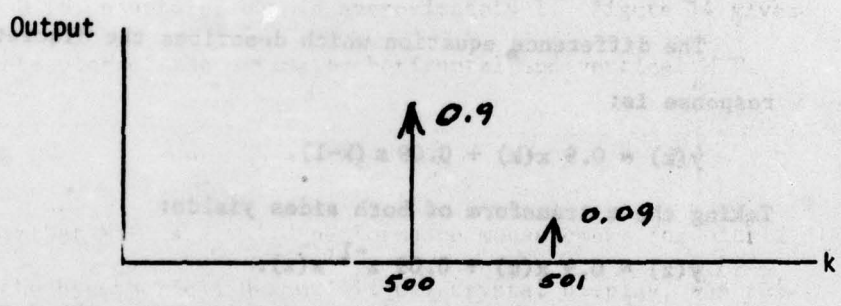
$$\frac{Y(z)}{X(z)} = H(z) = 0.9 + 0.09z^{-1} = \frac{0.9z + 0.09}{z} = \frac{0.9(z + 0.1)}{z}.$$

The pole-zero plot in the z domain is given in Figure 12. From this pole-zero plot, the frequency response magnitude can be obtained by ratioing the vector length of the zero to the "operating point" on the

Inspection of this response reveals it may more easily be analyzed as a discrete time-space system. The system is still that of Figure 10, however, only the sampled values of the input are shown. A single sampled input in Figure 10 is equivalent to a continuous delta function. The sampled system response to this delta function is shown in Figure 11. The input to the system is a single value, one, at time $k=500$. The response of the system is shown in Figure 11. The response of the system is shown in Figure 11. The response of the system is shown in Figure 11.



input at time to excite 500th element



output is at the 500th and 501st cell

Figure 11. Single Sampled Value Input and the Resulting Output

unit circle corresponding to the operating frequency over the vector length of the pole to the same point. If the operating frequency is chosen such that these vectors are on the unit circle, the above two represent the steady-state sinusoidal response of the system for the chosen frequency. A table of the pertinent values from Figure 12 is shown.

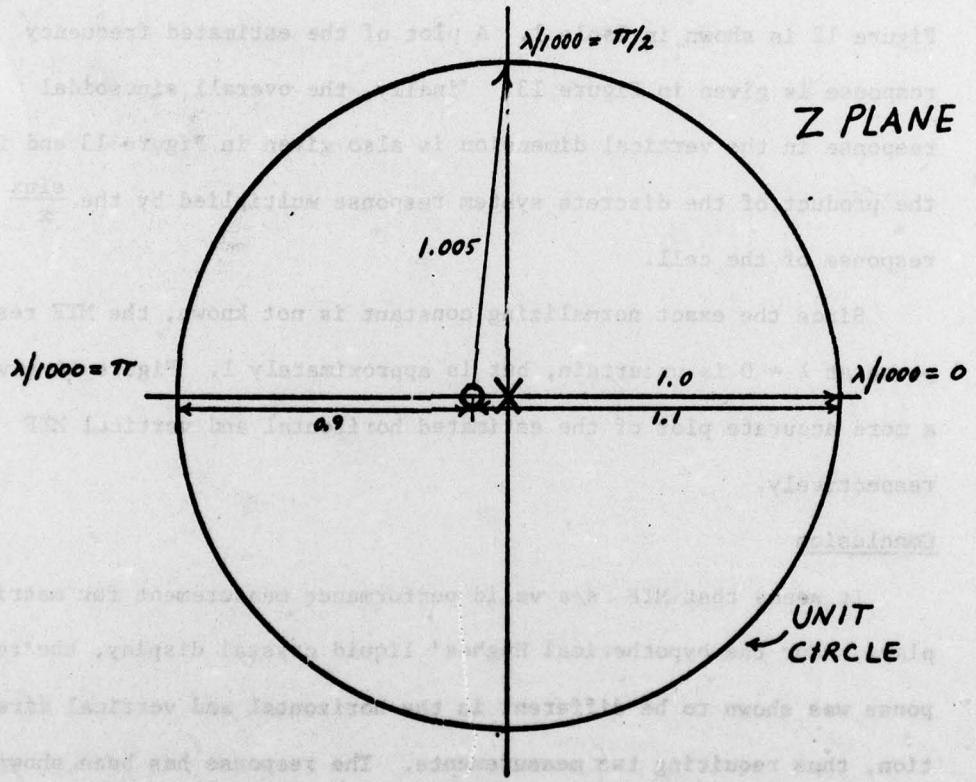


Figure 12. Pole-zero plot in Z plane of

$$\frac{0.9(z + 0.1)}{z}$$

unit circle corresponding to the operating frequency over the vector length of the pole to the same point. If the operating frequency is chosen such that these points are on the unit circle, the above ratio represents the steady-state sinusoidal response of the system for the chosen frequency. A table of the pertinent values from Figure 12 is shown in Table 1. A plot of the estimated frequency response is given in Figure 13. Finally, the overall sinusoidal response in the vertical dimension is also given in Figure 13 and is the product of the discrete system response multiplied by the $\frac{\sin x}{x}$ response of the cell.

Since the exact normalizing constant is not known, the MTF response at $\lambda = 0$ is uncertain, but is approximately 1. Figure 14 gives a more accurate plot of the estimated horizontal and vertical MTF respectively.

Conclusion

It seems that MTF is a valid performance measurement for matrix displays. For the hypothetical Hughes' liquid crystal display, the response was shown to be different in the horizontal and vertical direction, thus requiring two measurements. The response has been shown for a hypothetical 1000 X 1000 element display by using a linear systems approach.

This procedure was based on the assumption that the individual cell response was uniform across the display, and that the cell response did not overlap any adjacent cells. In the laboratory, this has been shown

Table 1

Pertinent Values Taken from Pole-Zero Plot of

$$\frac{0.9 (Z + 0.1)}{Z}$$

$op = 1 / \lambda X$ $= 1 / 0.001 \lambda =$	$V_z \rightarrow op$	$V_p \rightarrow op$	Ratio	Ratio X 0.9*
$1 / 0$	1.1	1.0	1.1	0.99
$1 / \pi/2$	1.005	1.0	1.005	0.90
$1 / \pi$	0.9	1.0	0.9	0.81

* from transfer function.

NOTE: The notation $V_p \rightarrow op$ and $V_z \rightarrow op$ represents the magnitude of the vector length from the pole to the operating point and the zero to the operating point respectively.

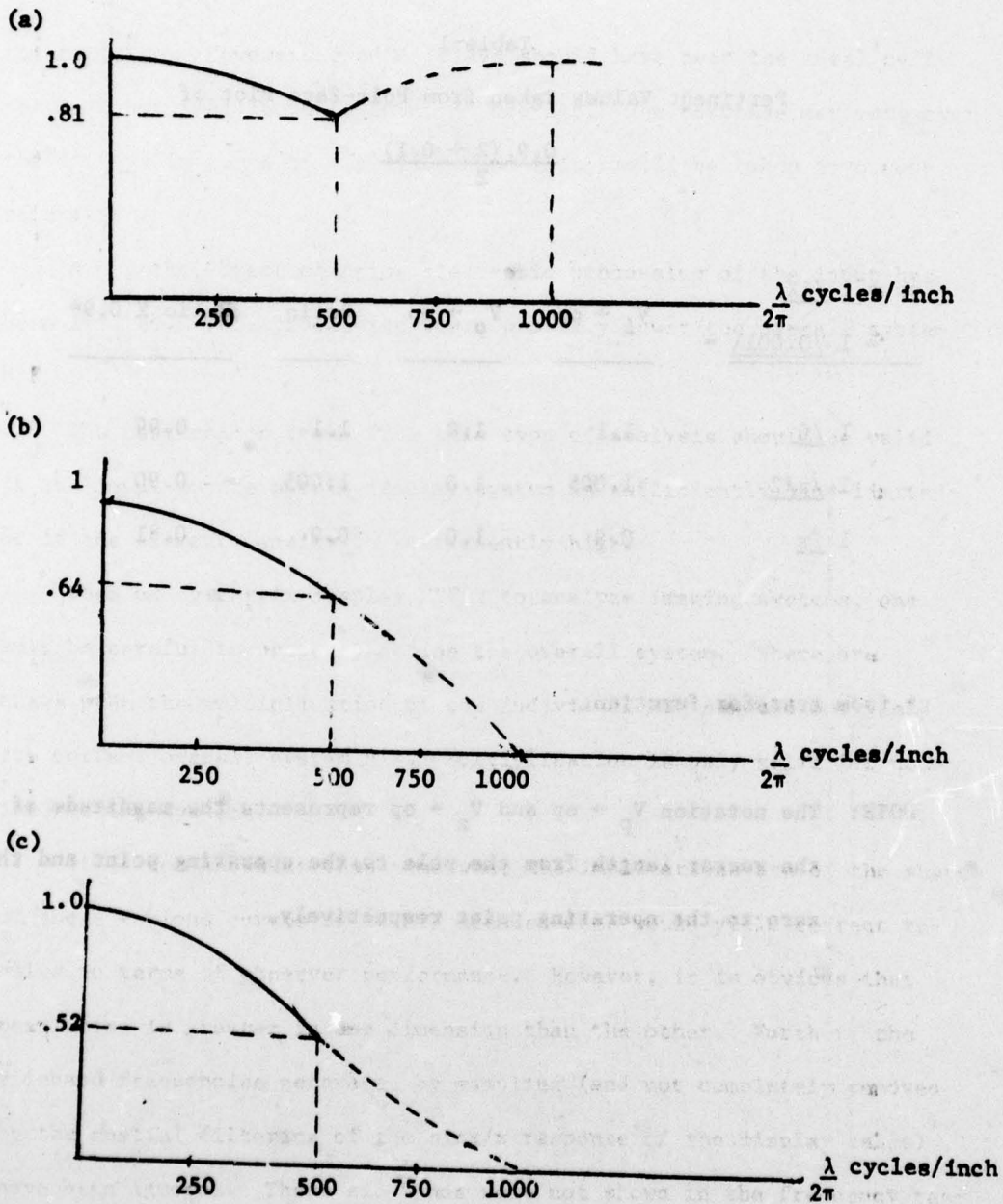


Figure 13. System Response

- (a) Response of Discrete System.
- (b) Response of Matrix (sinx/x).
- (c) Product of (a) & (b).

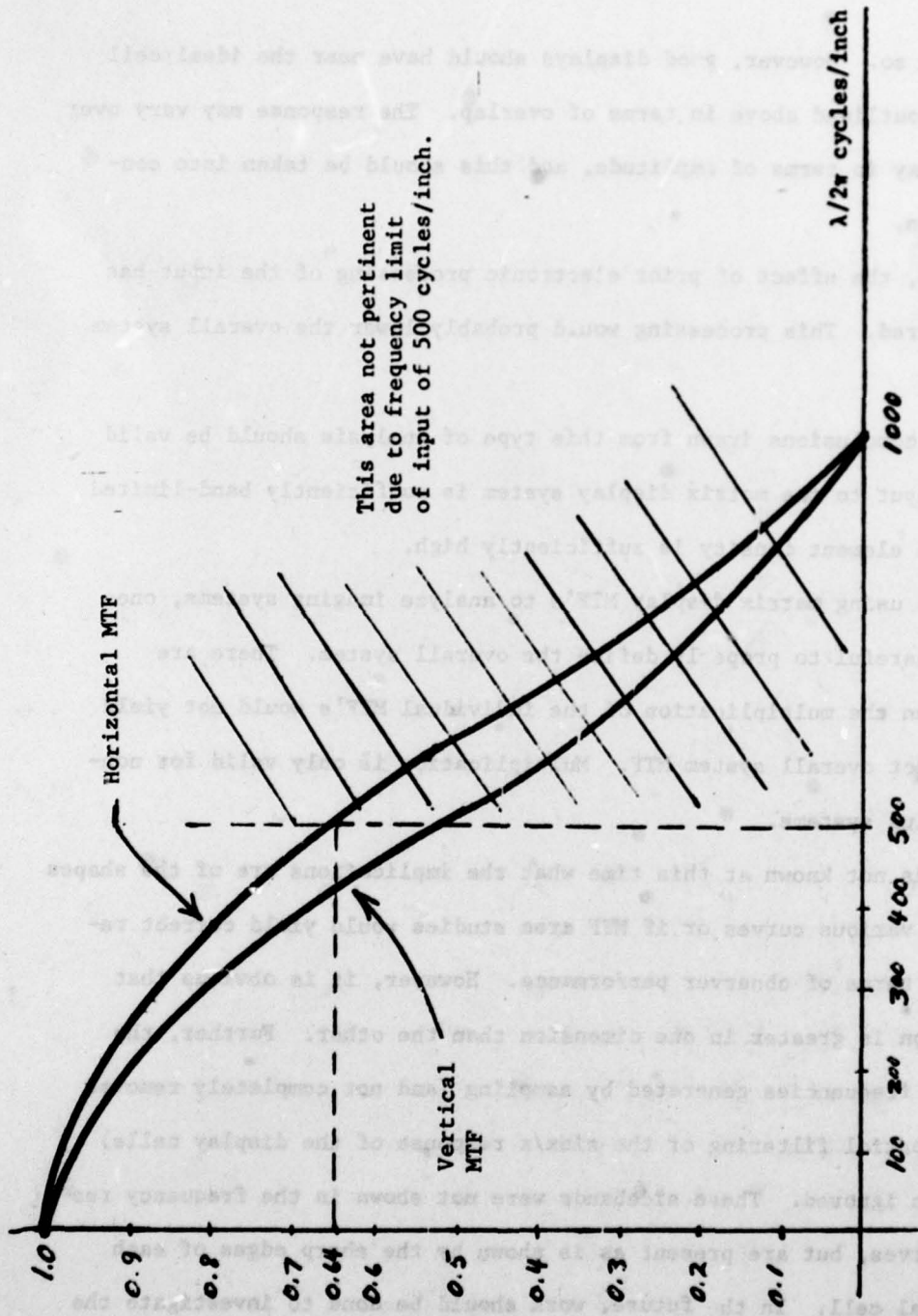


Figure 14.
 Estimated MTF of Hypothetical 1000 X 1000 Element Hughes' Liquid Crystal Display in Horizontal and Vertical Directions

not to be so. However, good displays should have near the ideal cell response outlined above in terms of overlap. The response may vary over the display in terms of amplitude, and this should be taken into consideration.

Also, the effect of prior electronic processing of the input has been ignored. This processing would probably lower the overall system MTF.

The conclusions drawn from this type of analysis should be valid if the input to the matrix display system is sufficiently band-limited or if the element density is sufficiently high.

When using matrix display MTF's to analyze imaging systems, one must be careful to properly define the overall system. There are cases when the multiplication of the individual MTF's would not yield the correct overall system MTF. Multiplication is only valid for non-interacting systems.

It is not known at this time what the implications are of the shapes of these various curves or if MTF area studies would yield correct results in terms of observer performance. However, it is obvious that resolution is greater in one dimension than the other. Further, the sideband frequencies generated by sampling (and not completely removed by the spatial filtering of the $\sin x/x$ response of the display cells) have been ignored. These sidebands were not shown in the frequency response curves, but are present as is shown by the sharp edges of each individual cell. In the future, work should be done to investigate the

implications of the shape of the MTF curves in terms of MTF area analysis. The effects of sideband generation should also be considered, especially if the matrix display is not sufficiently dense to place these frequencies outside or in a low response region of the human visual system MTF.

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