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Dynamic Sine Wave Response Measurements of CRT Displays Using Sinusoidal Counterphase Modulation

(Reprint)

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ABSTRACT

The current practice of basing the performance of cathode ray tube (CRT) displays solely on static image quality figures-of-merit fails to provide a valid assessment of a display's ability to reproduce real-world scenes where there is relative motion within the scene or between the sensor and scene. Techniques which provide assessment of a display's capability to reproduce spatial information in a dynamic environment are needed. One technique based on response to sinusoidal counterphase modulation is presented.

1. INTRODUCTION

A scene reproduced by an imaging system can be classified as static (passive) or dynamic (active). The term <u>static</u> implies there are no temporal characteristics attributed to the scene. Usually this means there is no motion within the scene. The term <u>dynamic</u> is used when relative motion exists either within the scene or between the sensor and the scene. By function, imaging systems always are dynamic in nature, i.e., there is always some time constant associated with the imaging process. When the scene is static, an imaging system will produce an image of the scene unaffected by motion (time) related interactions. However, when imaging a dynamic scene, the sensor's and display's inherent temporal characteristics in conjunction with those of the scene become important factors in the fidelity of the reproduced scene. For these reasons, techniques used to assess an imaging system's capability to faithfully reproduce a scene must reflect these temporal characteristics.

By convention, imaging systems have been characterized with static assessment techniques. This most likely is the result of experience in early photography where the film "speed" was very slow and objects in the scene were required to remain motionless. However, in imaging systems which use displays such as cathode ray tubes (CRTs), interactions between the temporal characteristics of the scene and the sensor are important factors in the display's resultant image quality. In spite of this fact, CRT display performance historically has been characterized using the same static assessment techniques as used with passive optical systems.[1] This static assessment approach provides an inadequate assessment of a CRT's performance for conditions where there is relative motion within the targeting scene or between the observer and the scene. This misrepresentation is a result of the interaction of the relative motion and the inherent temporal characteristics of the sensor and CRT. Temporal characteristics of the CRT include phosphor persistence, horizontal scan rate, vertical refresh rate, and amplifiers' bandwidths.

Head-mounted and head-tracked imaging systems, which employ CRT-based display technology, are particularly vulnerable to image degradation in dynamic imaging scenarios. The relative motion between an object in the imaging system's field-of-regard (FOR) and the observer's line-of-sight (LOS) can be hundreds of degrees per second. Self-contained night vision devices, such as night vision goggles (NVGs), display moving images at angular velocities that match those of the head. Velocities associated with head-tracked imaging systems are limited by the temporal response of the tracker and turret systems. Typically, 120 degrees/second is considered to be about the 95th percentile velocity for both azimuth and elevation movements, and 30 degrees/seconds is considered to be about the 50th percentile.[2]

The movement rates of concern are applicable to both continuous observation (tracking) and glances. The observer typically reduces head movement rates when there is a noticeable degradation in image quality that can be minimized by slowing the relative movement under the observer's control. Even when the objective is to glance in another direction, where the information between the initial and subsequent direction of gaze are of no interest to the observer, the duration of gaze motion is determined by cognitive factors rather than just the mechanics of orienting the head/eyes in the direction of interest. At suprathreshold conditions, the motion induced image quality reduction may be of little consequence. However, when the sensor, display, and observer are functioning near their operating limits, even a modest reduction in image quality may be of considerable consequence but not readily apparent to the observer. An electro-optical system which meets performance requirements during a static bench test actually may provide much less scene information than expected when in actual use.

Contrast is one physical metric commonly used by both vision scientists and engineers for describing image quality. Contrast, generally defined as the difference between the brightest and darkest regions of a scene, can be expressed in a number of ways, some of which are more appropriate than others for specific applications. For CRT displays, modulation contrast, or Michelson contrast, is often the most appropriate metric for describing their capacity to convey relative luminance. Modulation contrast (M_c), defined as

$$M_c = (L_{max} - L_{min})/(L_{max} + L_{min}),$$

where L_{max} is the maximum luminance and L_{min} is the minimum luminance, is a common figure-of-merit used to quantify a display's image quality.[3] Modulation contrast can be related to the integer number of gray scales an analog display is capable of reproducing. For CRT displays, discriminable gray scales usually are defined as the levels of luminance differing by the square root of two. The relationship between gray scales and modulation contrast associated with this definition is depicted in Figure 1.

The ability of a display to reproduce contrast is spatial frequency dependent, and as we shall see also is temporal frequency dependent. Spatial frequency refers to the rate of luminance change over space, typically expressed as the number of sine wave cycles per display width. Temporal frequency refers to the rate of luminance change over time, which is expressed in Hertz. When modulation contrast values are measured for a specific display, expressed as ratios to the input modulation, and plotted as a function of spatial frequency, the resulting curve (Figure 2) is referred to as the display's modulation transfer function (MTF). For a static CRT image, the MTF, measurable by any of a number of available techniques,[4] can be interpreted as the MTF for the scenario where the relative motion within the scene is zero.

The modulation contrast values and resulting MTFs of a static image and one with a relative motion of 30 degrees/second can be quite different for a CRT display. For a static image, the modulation contrast values for high spatial frequencies normally are lower than for low spatial frequencies. Similarly, the modulation contrast values for high relative velocities normally are lower than for low relative velocities. The modulation contrast value of a high velocity, high spatial frequency object easily can fall below the human visual threshold while the same high spatial frequency object at rest can have a value above this threshold. A preliminary model which describes a family of MTF curves, with a separate curve for different values of relative velocity, has

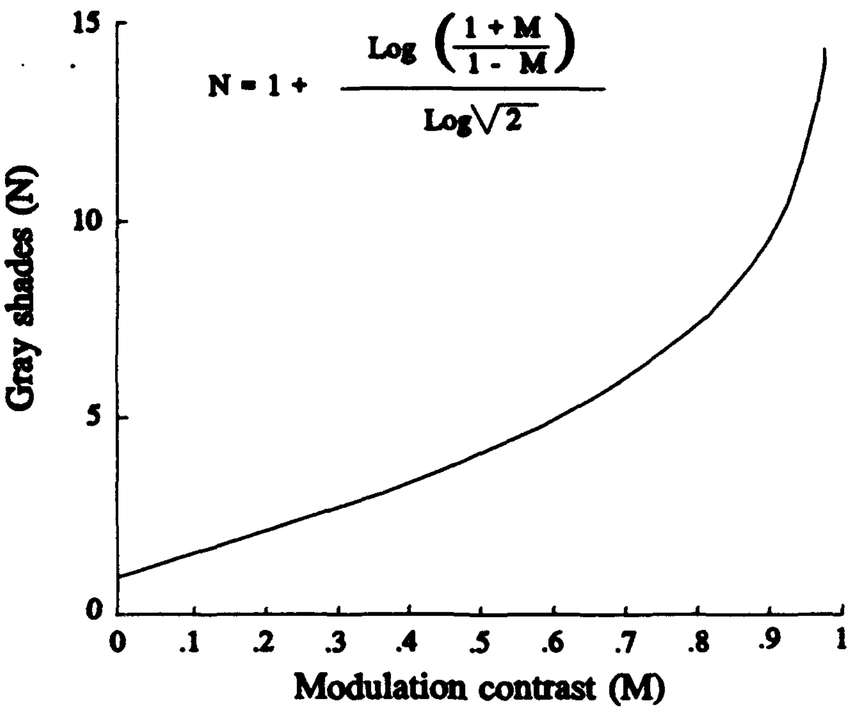

Figure 1. Relationship between gray scales and modulation contrast.

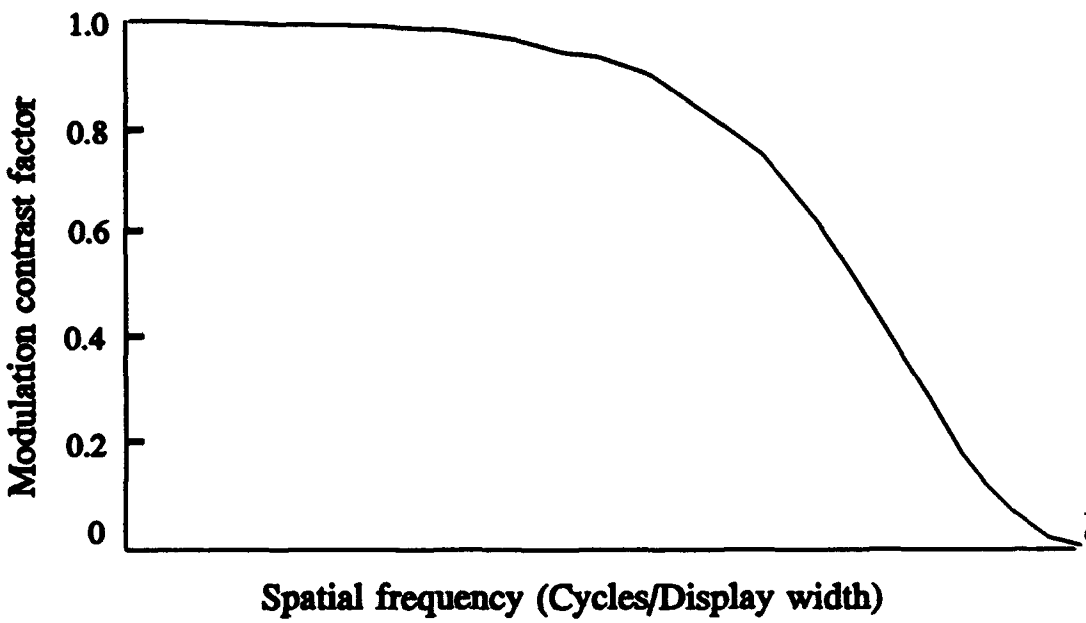

Figure 2. Typical modulation transfer function curve.

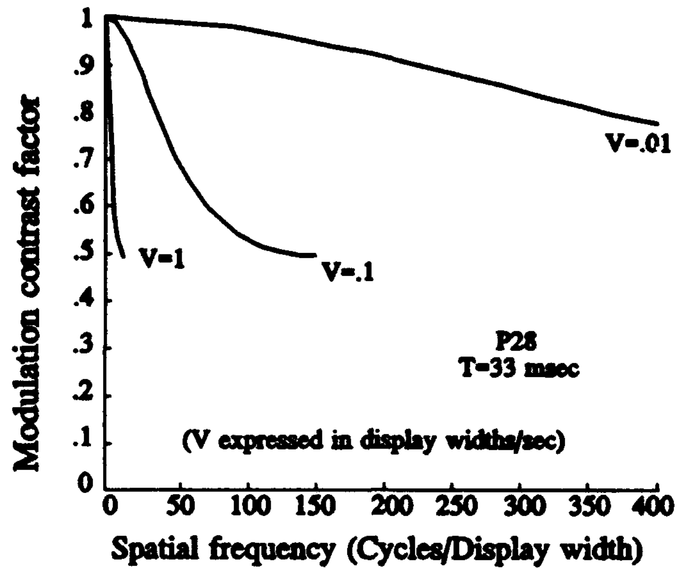

Figure 3. Modeled dynamic modulation transfer curves.

been developed for CRT displays by Rash and Becher.[5] The model predicts reductions in MTF resulting from the interaction of target/scene relative motion and the display's temporal characteristics of scan rate and phosphor persistence. Figure 3 depicts a modeled family of curves for a P-28 phosphor (70 ms, 10%) in a CRT display with a vertical frame period of 33 ms; three curves which are representative of three relative velocities are shown.

In order to accurately describe the performance of CRT displays used in dynamic environments such as driving, pilotage, or target acquisition systems, these displays must be characterized for dynamic images. Measuring the display's static performance and expecting it to be representative of its performance for moving imagery is unrealistic. The actual performance may be degraded significantly from the inflated expectations based on the static assumption. The loss of gray scale and high spatial frequency information may lead to dire consequences. As an example, during the early design phase of the AH-64 Apache attack helicopter, an incident was reported where the test pilot, viewing imagery on the Integrated Helmet and Display Sighting System (IHADSS) helmet-mounted display, lost sight of some small branches in his field-of-regard (FOR) during a nap-of-the-earth (NOE) flight. This resulted in a blade strike and damage to the aircraft. The head-coupled display with its P-1 phosphor was suspected to be the source of the problem. The 24-millisecond (ms) persistence (10%) of the P-1 phosphor did not have the temporal response required to display the high spatial frequency branches during moderate head movements. When the CRT phosphor was replaced by a lower persistence P-43 phosphor (1.2 ms, 10%), the branches were visible under the same conditions. The static MTF of displays with P-1 and P-43 phosphors were similar, but the dynamic characteristics of the phosphors made the difference between success and failure.

Verona[4] has suggested the most accurate method of obtaining the static MTF of a CRT display is the discrete sine wave frequency response method. This method involves generating a sine wave modulation pattern at a selected low spatial frequency (e.g., 2-3 cycles/display width) on the CRT, scanning the pattern using a scanning microphotometer, and calculating the modulation contrast ratio value. While maintaining a constant modulation input signal, this procedure is repeated for ever increasing spatial frequencies until the modulation contrast approaches zero (typically less than 0.05). Plotting these values as a function of spatial frequency provides the static MTF curve—to be thought of as the first of a series of dynamic MTF curves, i.e., for a relative velocity value of zero. To fully characterize the display, additional dynamic MTF curves need to be developed for other velocity values. Two techniques, the counterphase modulation and the drifting sine wave techniques, can be used to obtain these curves. The drifting sine wave technique is based on spatial sinusoidal patterns which continuously change in phase, resulting in an apparent movement of the spatial patterns on the display. The counterphase modulation technique involves placing multiple spatial frequencies on the display (one at a time) and having the white and black portions of each cycle alternate between their maximum or minimum intensities (contrast reversal). The counterphase modulation technique is described in this paper.

2. DISPLAY SETUP

To characterize a CRT display, the operating parameters of the display must first be set for the anticipated operating environment. This is true regardless of the technique used to measure the display's performance. The signal levels, line rate, focus, peak luminance (brightness), contrast, and image size/aspect ratio are some of the more important operating parameters that can influence the display's performance. The video test signals should match the anticipated operating video levels and timing. RS-170A NTSC or RS-343 standards are appropriate for most applications. If the display is to be used in more than one environment, for example under both day and night conditions, then two sets of performance measurements are appropriate, one set for day viewing and the other for night viewing conditions. Similarly for the line rate, if the display will be used to present both 875- and 525-line video, it must be tested at both line rates. Four sets of data would be required if both line rates are used under both day and night conditions.

For the data reported here, a Conrac model SNA 14/N monitor operating with RS-170A NTSC (525-line rate) video was evaluated under simulated night conditions (in a fully darkened laboratory). The monitor was fitted successively with CRTs with P-44 (1.2 ms, 10%) and P-1 (24 ms, 10%) phosphors. Following adjustment of focus and aspect ratio using the manufacturer's recommended procedures, the display's brightness and contrast were set using the following procedure.

First, a predetermination of peak brightness was made. For the simulated night environment, a value of 15 footlamberts was chosen. For a desired white/black ratio of 100:1, this required the black level luminance to be 0.15 footlambert. Brightness and contrast controls were adjusted to their minimum settings (fully counterclockwise). Inputting a low spatial frequency square wave 1-volt peak-to-peak video signal, the brightness control was increased until the raster was just barely visible. The contrast control then was advanced to a setting which produced a 15 footlamberts luminance value at the peak of the pattern (maximum video level). The black level luminance (minimum video level) was examined to see if the 0.15 footlambert value was present. As required, the brightness and contrast controls were adjusted alternately to achieve the 100:1 ratio. The luminance values associated with the minimum and maximum video levels were measured using a Minolta 1-degree luminance meter. These values were 0.15 and 15 footlamberts, respectively.

3. COUNTERPHASE MODULATION TECHNIQUE

This technique attempts to take advantage of the flexible and robust nature of the computer as a signal generating imaging source. With such a configuration, software can be written to generate custom test patterns for static or dynamic presentations on the display. The modulation contrast of the patterns can be measured photometrically as the patterns vary in spatial and temporal frequency.

The displays used in the evaluation were driven by computer generated static and dynamic sine wave spatial patterns with the long dimension of the pattern at a 90° angle (vertical) to the display's scan line structure. For the static case, spatial frequency sine wave patterns of selected frequencies were generated and presented on the display. The modulation contrast measurements were made using the peak and trough luminance values obtained from the resulting display image. For the dynamic case, the spatial sine wave patterns also were modulated temporally at selected sinusoidal frequencies. One temporal cycle of the stimulus consisted of the luminance at a position on the display changing from its brightest value to its darkest value and back to its brightest value (counterphase). As a result, the luminance variations on the display were sinusoidal in both spatial and temporal domains.

This temporal sinusoidal test stimulus is different from a square wave counterphase flicker stimulus where the luminance at a point on the display is alternated in a square wave fashion with abrupt transitions from bright to dark. The sinusoidal variation provides a purer stimulus since there is a strong tendency for the turn-on in the square wave input to overshoot in luminance. This overshoot causes the modulation to be exaggerated, i.e., the peak luminance for high spatial frequencies becomes greater than would normally be caused by an input signal within the bandwidth limitations of the display. This overshoot easily can be interpreted during modulation transfer function analysis as an improved high frequency response when, in fact, it is an artifact of the display's response to the fast rise time stimulus and subsequent overshoot. This same result is not apparent when the turn-off portion of the square wave stimulus is analyzed.

A pictorial diagram of the experimental setup is presented in Figure 4. Stimulus generation was performed using a computer graphics workstation which was linked to a video scan converter. Measurement of the resulting display peak and trough luminances, which were used to calculate the modulation contrast values, was accomplished using a combination of collection optics, a photomultiplier tube (PMT), a high voltage supply, electronic filters, and a digital storage oscilloscope.

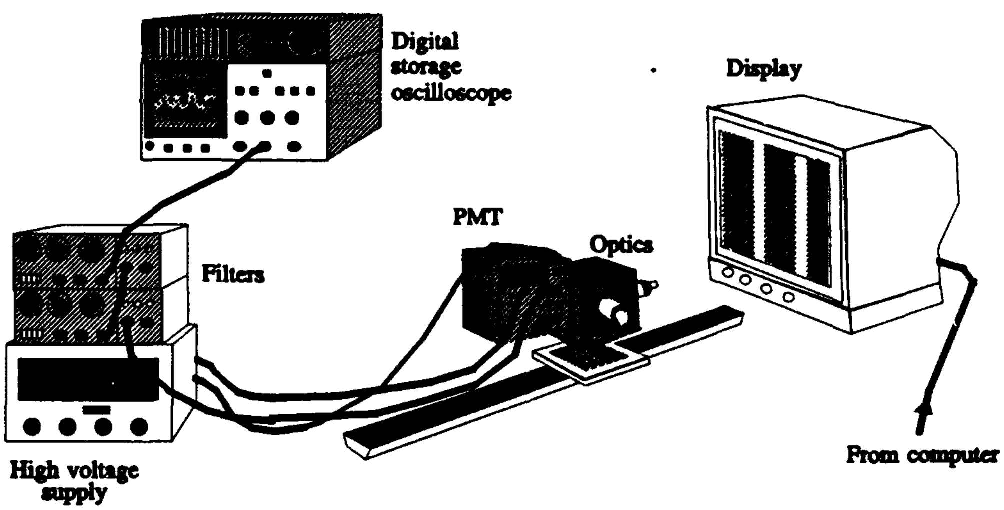

Figure 4. Pictorial diagram of the experimental setup.

Stimulus patterns were generated with a Hewlett-Packard model HP-98731 Turbo-SRX computer graphics workstation. The output of the computer was fed to a Folsom Research, Inc. model 8910 color graphics converter which produced a RS-170A NTSC video signal. This video signal was used to drive the display under evaluation. The software which produced the stimulus patterns was written in the C programming language running in an UNIX environment. Except for aliasing effects, the patterns theoretically could be generated at any desired spatial frequency and presented at any temporal frequency at or below 30 Hertz. For the evaluation presented here, combinations of the spatial and temporal frequencies presented in Table 1 were used. By convention, contrast measurements were not made for combinations beyond the point where the modulation contrast (M_c) dropped off to less than 5 percent (0.05) or display artifacts were encountered.

Table 1.

Spatial and temporal frequencies

Spatial (Cycles/display width)	Temporal (Hertz)
3.6, 7.1, 10.7, 14.2, 17.8, 21.3, 28.4, 32.0, 35.6, 42.7, 64.0, 71.1, 85.3, 106.0, 128.0, 142.2, 160.0, 177.8	0, 1.875, 3.75, 5.0, 7.5, 10.0

The physical and electrical characteristics of the collection optics, PMT, and high voltage supply (which together function as a photometer) are critical to the interpretation of the measurements. A slit aperture is recommended. Its width should be approximately 10 times smaller than the highest spatial frequency measured in the object plane and its length should cover at least approximately 5 display scan lines. A 25 X 8000 micron width to length ratio was used for this evaluation. The objective lens power determines the effective width and length in the objective plane. A 5X microscope lens was used to give an effective 5 X 1600 micron measurement slit on the display screen. If the effective slit width is too large, the modulation amplitude measurements will be artificially low. If the slit width is too small, the luminance signal level will be low and noisy.

A Gamma Scientific, Inc. model DR-2 digital radiometer, model D-46A PMT assembly with 4 MHz high frequency amplifier, and model 700-10 photometric microscope with a 25 X 8000 micron slit were used to convert the spatial and temporal luminance values into an electrical signal which was measured using a Tektronix model 2440 digital storage oscilloscope. The model DR-2 radiometer was used only as a source of high voltage for the PMT and a high voltage value of 700 volts was used. The output of the high frequency amplifier of the PMT was filtered by two Frequency Devices, Inc. model 901F electronic filters before being fed to the oscilloscope. The filters, connected in series, acted as a low pass filter with a cutoff frequency of 35 Hertz and provided 40 dB of gain. The temporal response of the photometer is very critical for the dynamic measurements. The limited range of response speeds typically encountered in off-the-shelf photometers is inadequate for reliable dynamic measurements. Therefore, the video or high frequency output of the photometer was used. The electronic filters provided amplification and filtered out high frequency noise, improving the signal-to-noise ratio. The output of the filter was displayed on a digital oscilloscope.

To evaluate the static case, zero Hertz temporal frequency, contrast measurements were made over the spatial frequency range of approximately 3 cycles per display width to the cutoff frequency, where the modulation contrast dropped off to less than 5 percent. For each spatial frequency, a peak of the sine wave was positioned in front of the photometer and the resulting maximum output was read from the display of the oscilloscope and recorded. Then a trough of the sine wave was positioned and the resulting minimum output was read and recorded. These data, when used to calculate the contrast values, represent the sine wave response of the display for the static image condition.

For the dynamic measurements, a temporal frequency was selected and an input signal was applied to the display at each spatial frequency. For each spatial frequency, the photometer output signal was acquired using the storage oscilloscope. From the digitized waveform, the peak and trough values were obtained and used to calculate the modulation contrast value. This procedure was repeated for each temporal frequency.

Modulation transfer ratios were calculated from the input and output modulation contrast data for all spatial and temporal frequency combinations and presented as MTF curves.

4. PERFORMANCE DATA

MTF curves for the P-44 and P-1 displays are presented in Figures 5 and 6, respectively. The family of curves for the P-44 phosphor did not show any significant differences between the display's performance for the various temporal frequencies tested. However, the P-1 curves showed significant differences for the 7.5 and 10.0 Hz temporal frequencies.

The lack of definition between the dynamic MTF curves for the P-44 phosphor was expected since the 1.2 ms persistence value characterizes P-44 as a medium-short persistence (fast) phosphor. The performance of this phosphor did not noticeably degrade as the temporal frequency was increased. For the P-1 phosphor with its 24 ms (medium) persistence, the dynamic MTF curves for 7.5 and 10.0 Hz were significantly different from the other temporal frequencies. Although not statistically significant, the trend in the contrast modulation values and resulting MTF curves was that of having consistently greater values for the lowest temporal frequency (1.875 Hz) than for the static condition (0 Hz). This was true for both display phosphors. It is believed this is a result of a low-frequency response defect present in many AC-coupled video amplifiers.[6] (Note: The same drive electronics was used for both CRT phosphors.)

5. SUMMARY

The sinusoidal counterphase modulation method proved capable of assessing a display's dynamic performance. This was demonstrated for two phosphor displays, one (P-44) for which no degradation was expected and one (P-1) for which degradation due to motion has been documented. However, this technique exhibited several limitations which reduced its desirability. First, the technique was very tedious and time consuming. Considerable patience and effort were required in reading the peak and trough values from the

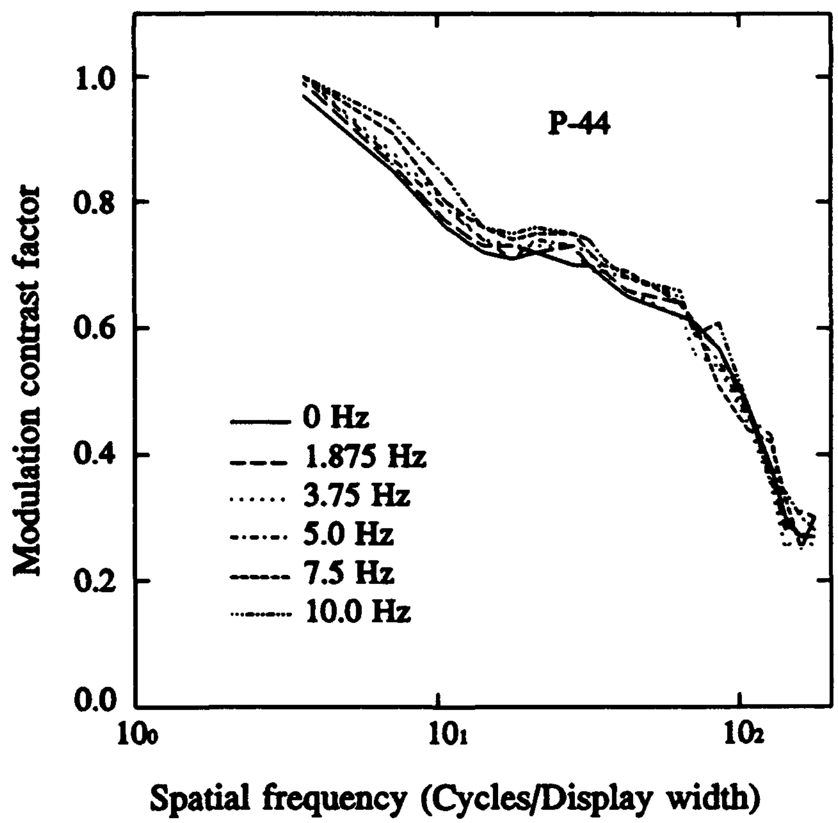

Figure 5. MTF curves for P-44 phosphor display.

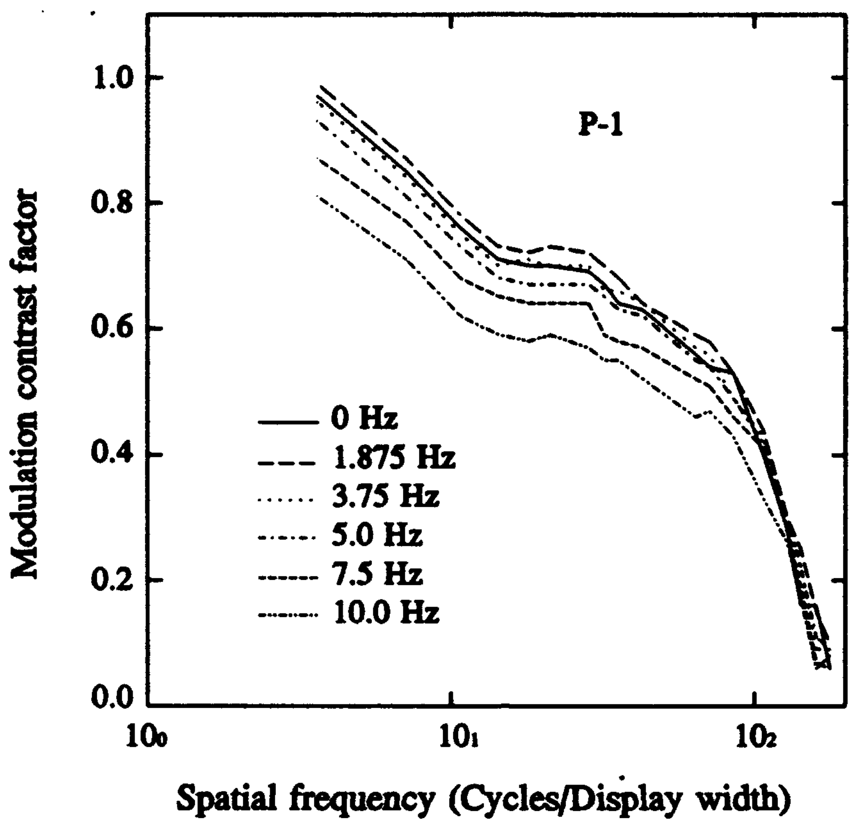

Figure 6. MTF curves for P-1 phosphor display.

storage oscilloscope waveforms. The average time required to complete measurements for the spatial and temporal frequency combinations in Table 1 was approximately 2-1/2 hours. Second, while the use of the computer graphics workstation provided flexibility in the generation of spatial and temporal patterns, the conversion of the workstation's RGB digital output into 525-line rate video resulted in a test signal which was nonuniform in its modulation. This limitation required additional measurements and had to be compensated for in the MTF calculations. In addition, this signal contained a beat frequency which caused some difficulty in the ability to measure waveforms accurately for the higher spatial frequencies. In spite of these limitations, the sinusoidal counterphase modulation technique provides a functional approach to assessing a CRT display's performance in the temporal domain.

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