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Effects of Form Errors of a Micromirror Surface on the Optical System of the TMA™ (Thin-film Micromirror Array™) Projector

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ABSTRACT

The projectors using liquid crystal display (LCD) have faults such as low optical efficiency, low brightness and even heat generation. To solve these problems reflective-type spatial light modulators based on MEMS (Microelectromechanical Systems) technology have emerged. Digital Micromirror Device™ (DMD™), which was already developed by Texas Instruments Inc., and Thin-film Micromirror Array™ (TMA™), which has been recently developed by Daewoo Electronics Co., are the representative examples. The display using TMA™ has particularly much higher optical efficiency than other projectors. But the micromirrors manufactured by semiconductor processes have inevitable distortion because of the limitations of the manufacturing processes, so that the distortions of their surfaces have great influence on the optical efficiency of the projector. This study investigated the effects of mirror flatness on the optical performance, including the optical efficiency, of the TMA™ projector. That is to say, as a part of the efforts to enhance the performance of the TMA™ projector, how much influence the form errors of a micromirror surface exert on the optical efficiency and the modulation of gray scale of the projector were analyzed through a pertinent modeling and simulations.

Key Words: Spatial light modulator, mirror flatness, optical efficiency, modulation of gray scale, diving tilt angle, virtual plane, transmittance function, Fourier transform

1. Introduction

From old times human wanted to watch lifelike moving images and this desire gave rise to various optical implements in the 19th century. One of these is the motion picture, which made man's dream at least come true but he also wanted to watch what was happening in the other side of the world. So, human invented the electronic projection display like cathode ray tubes (CRT). With the help of this technology, man simultaneously watched the things all over the world. After that, people used the electronic projection display technology as a part of the efforts to bring live television programs to big screens at theaters, but the big screens were not satisfactorily bright. Although the LCD technology was devised to solve these problems, it needs a dark atmosphere due to its low optical efficiency and even has fault like heat generation. With the rapid development of MEMS (Microelectromechanical Systems) technology, however, reflective-type light valves, which could replace the previous light valves, have been invented. Digital Micromirror Device™ (DMD™), which was already developed by Texas Instruments Inc., and Thin-film Micromirror Array™ (TMA™), which has been recently developed by Daewoo Electronics Co., are the representative examples, which consist of an array of micromirrors.(1, 2)

As the term "reflective-type" is suggestive, they reflect the light from light source directly to screen, so that the projectors using DMD™ or TMA™ are superior to others using the transmissive-type light valves like

LCD in terms of brightness, resolution and pixelation. Especially, they have higher optical efficiencies than any others and are expected to make a great contribution to the development of display industry.(3, 4, 5)

The core elements of these projectors are naturally the mirror chips and sacrificial layers are exploited to make the micromirrors with as plane surfaces as possible. But, because of both the incomplete planarization of the sacrificial layers and the residual stresses of micromirrors made of aluminum, the surfaces of micromirrors are distorted to some extent. As a result, the mirror flatness gets to influence on not only its optical efficiency but also its modulation of gray scale.(6)

Thus, in this research, was examined how and how much the form errors of a micromirror surface influence on the optical performance of the TMA™ projector. First, a reasonable "modeling" based on the theory of wave optics was done for the problem-solving. Through the proposed method of simulation were quantitatively calculated the optical efficiency and the changes of gray-scale value with regard to tilt angles of the measured micromirror. And then, after carrying out an experiment with the optical system equivalent to the TMA™ projector, the simulated values were compared with the experimental values. Together with those, changes of both the optical efficiencies and the gray-scale lines were looked into as the form errors of the surface of the measured micromirror increase more and more.

2. Thin-film Micromirror Array™

2.1 Structure and Actuation

One side of a square micromirror within a TMA™ chip is 97 μm (VGA) or 48 μm (XGA) in length. Fig. 1 is a SEM picture which shows a part of micromirrors of a VGA-type TMA™ chip. An actuating part of the cantilever-type is laid under each micromirror, so that each of the micromirrors functions as a spatial light modulator.(6)

Fig. 2 is illustrating the motion of a cantilever, which consists of a supporting layer, a bottom electrode, a piezoelectric layer and a top electrode consecutively from bottom to top. If voltage is applied between the two electrodes, the PZT layer comes to contract horizontally and expand vertically, so that the whole cantilever deflects vertically, because the supporting layer is relatively thick and the neutral plane of the cantilever is shifted in the direction of the bottom electrode. Thus the deformation of the PZT layer makes the micromirror, attached to the end of the cantilever, rotate. And the tilt angle of the micromirror is linearly proportional to the applied voltage.(7)

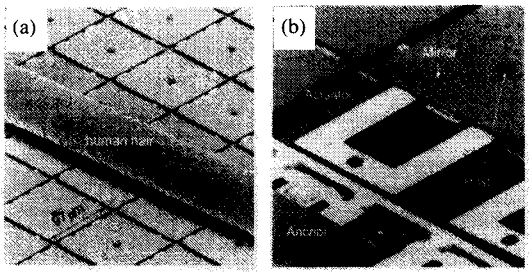

Fig. 1 SEM pictures of TMA™ mirrors (a) with a human hair and (b) with some intentionally removed(6)

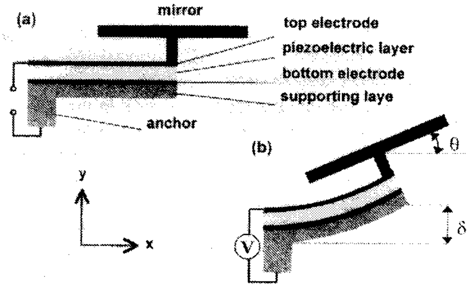

Fig. 2 Actuation principle of a TMA™ cantilever(7)

2.2 Light Modulation

Fig. 3 explains the principle of gray-scale modulation of the TMA™ projection system. The light of a source lamp passing through the source stop reflects on a micromirror surface and the reflected light forms an image equal to the broad source on the projection-stop plane. If the tilt angle of the micromirror changes, the image comes to be shifted horizontally. Now that only the amount of light passing through the projection stop is able to reach the screen, the intensity of light on the pixel of the screen becomes different according to tilt angles of the corresponding micromirror. Since the tilt angle of a micromirror is supposed to change linearly according to applied driving voltage, the gray scales of the TMA™ projection system are modulated by precisely controlling the driving tilt angles or the corresponding driving voltages.(8)

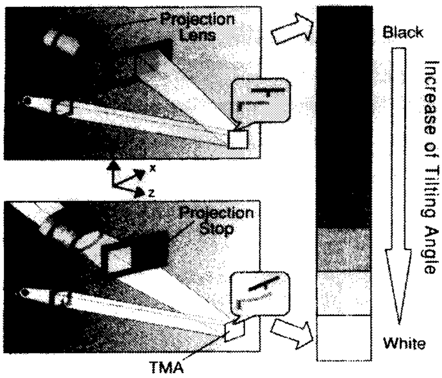

Fig. 3 Light modulation of the TMA™ projection system(8)

2.3 Optical System of the TMA™ Pixel

To carry out researches into the effects of mirror flatness on the optical system of the TMA™ projector, we need to understand the TMA™ pixel optics before anything else. Fig. 4 shows in details the TMA™ pixel optics which is defined as the optical system from the source stop to the projection stop. If we set the line passing through the center of the collimating lens, projection stop and projection lens, the center of the source stop is inclined at 6 degrees from the optical axis. Considering when the micromirror in Fig. 4 has a tilt of 3 degrees, the spherical wave coming out from the point source which is located at the center of the source stop becomes a plane wave by means of the collimating lens which is placed right in front of the mirror chip, and the plane wave is reflected by the micromirror, and then the reflected wave, by means of the same collimating lens, gets together at the center of the projection stop which is the focal plane of the lens. Also the light from the point source right below the center of the source stop gets together at the point right above the center of the projection stop by the law of reflection. In the same manner, each point at the broad source corresponds symmetrically to each point at the projection-stop plane about the line inclined at 3 degrees from the optical axis. When the micromirror has a tilt of 0 degree, the broad source at the source stop and the image at the projection stop likewise becomes symmetric about the optical axis. In other words, the broad source could be said to be imaged on the projection-stop plane by the micromirror. So, if we think of the tilt angle of the micromirror and the angle at which the source stop is inclined, it is easily understood that the image becomes gradually distant from the optical axis as the tilt angle varies from 3 degrees to 0 degree.

The following is an interpretation for the shape of image formed at the projection-stop plane in terms of wave optics. Supposing that the micromirror is perfectly flat and the light from a point source is monochromatic, the image of the point source is directly related to the Fourier transform of the geometrical shape of the micromirror because the reflected light by the micromirror is, at least ideally, a plane wave. This analysis can be applied to any other point sources as well as the point source at the center of the source stop. Therefore, the image of the broad source is simply the superposition of the intensity distributions formed by every point source, because the light emerging from the source stop comes from a primary light source and every point source at the broad source could be regarded as having no spatial coherence mutually. In addition, the above interpretation can be applied to any other micromirrors within the mirror chip. Thus, whether the micromirror is located exactly on or off the optical axis, the micromirrors with the same tilt angle create their corresponding images at the same position on the projection-stop plane, provided there is no aberration at all in the optical system.

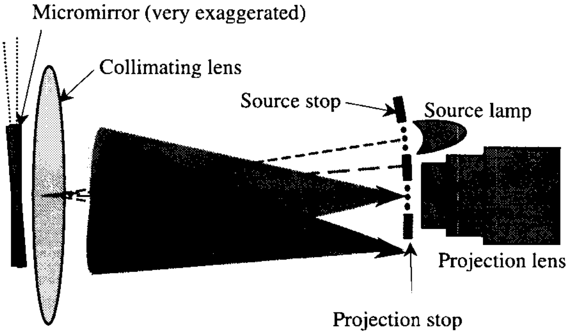

Fig. 4 Configuration of the TMA™ pixel optics

3. Modeling

If the surface of a micromirror has some distortion, the reflected wave by the micromirror is certain to be deviated from a plane wave which otherwise it would be. From the standpoint of wave optics again, it can be easily forecast that the image of the point source would be somewhat deviated from the one directly related to the Fourier transform of the geometrical shape of the micromirror. Fig. 5 accounts for the relationship in details between the distortion of a micromirror surface and the image at the projection-stop plane in terms of wave optics. If a micromirror has a sinusoidal waviness and all the incident plane waves are perpendicular to the micromirror, the transition of light in the TMA™ pixel optics could be described as in Fig. 5. Right after an incident plane wave is reflected on the micromirror surface with sinusoidal waviness, its wavefront would become one with sinusoidal waviness which is similar to the distortion the micromirror has. Assuming then that there is a virtual plane right in front of the micromirror surface and considering the complex field distribution on the virtual plane, the amplitude distribution could be presumed to be almost constant but the phase distribution is not constant. The phase distribution on that virtual plane depends on the extent of mirror flatness and the phase values are able to be calculated from optical path differences between the virtual plane and the distorted wavefront with sinusoidal waviness.

As it is displayed clearly in Fig. 5, for example, the optical path of the ray A is longer than that of the ray B by 2h, where h is the peak-to-valley value of the micromirror. Similarly the optical path of the ray C or E is longer than that of the ray D by 2h. Accordingly the phases of point a, c and e are the same one another and the phases of point b and d are the same each other, but the phase of point a, c or e is different from that of point b or d. In this way the phase distribution at the virtual plane comes to have sinusoidal distribution when the surface profile of a micromirror has a sinusoidal waviness. So, the phase distribution at the virtual plane of interest is able to be obtained from the information of the heights of the surface profile of the micromirror. If we regard the distorted wave as the one coming through a certain phase grating, then the field distribution with amplitude and phase information at the virtual plane could be set to be the corresponding transmittance function. Consequently the intensity distribution of the image of a point light source is equivalent to the square amplitudes of the Fourier transform of the very transmittance function. And, because of spatial incoherence of the point sources at the broad source, the image of the broad light source of interest is just the superposition of the images of each point source.

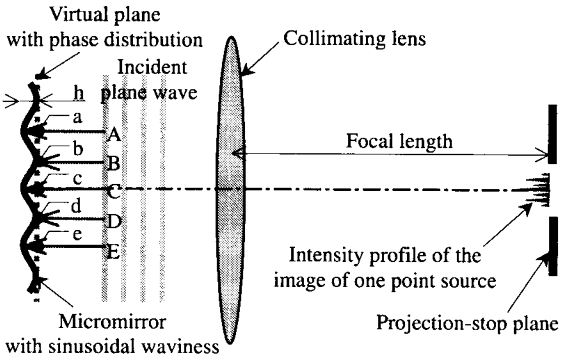

Fig. 5 Simplified model of Fig. 4

4. Simulations and Experiments

4.1 Process for the Whole Image

Fig. 6 shows how the whole intensity distribution at the projection-stop plane is calculated. This figure, where the collimating lens is divided into two in order to understand its role easily though it is actually just one, illustrates the case that the source stop and the projection stop are symmetrical about the normal line of a micromirror with a tilt of 3 degrees. The spherical wave coming out from the point source S_b at the center of the source stop becomes the plane wave P_b by the collimating lens and the plane wave P_b is transformed into the distorted wave W_b after reflection. Since the profile of the distorted wavefront would be sure to be similar to that of the micromirror surface, the phase distribution at the virtual plane is computed by

$$\phi = (2\pi/\lambda)\, 2(\Delta_{max} - \Delta), \qquad (1)$$

where Δ is the heights of the measured micromirror and λ is the considered wavelength of light. And the transmittance function t_b, which the distorted wave W_b undergoes, is obtained by

$$t_b = \exp[i\phi]. \qquad (2)$$

Now that W_b is imaged by means of the same collimating lens at the projection-stop plane, the complex field distribution is gained from the Fourier transform of the very transmittance function t_b and then the whole intensity distribution I_b is acquired by squaring the amplitudes of the complex values. In the same manner, each intensity distribution I_a and I_c is able to be acquired. Thinking of the broad source as having a total of about

2500 (50 by 50) point sources, all the intensity distributions that every point source creates are evaluated. And then the total intensity distribution, which is so far of our interest, is estimated only through the superposition of all the intensity distributions.

It is the last thing to overlook that the lights from arbitrary point sources do not have the same incident angle of 90 degrees but a little different incident angles one another deviated from 90 degrees. When a micromirror has some distortion, the incident plane waves with their own incident angles of inclination undergo different transmittance functions one another. The optical path in case of a distorted micromirror is shorter than that in case of a flat one by $2\Delta\cos\gamma$, where γ is the incidence angle and Δ is the height of the micromirror. Consequently, for instance, I_a, I_b and I_c in Fig. 6 are not exactly the same mutually. Therefore, in order to acquire the exact image of the broad source, the incidence angles are required to be first computed from the positions of the point sources, and from the information the optical path differences have to be obtained at virtual planes, and then the transmittance functions corresponding to each incidence angle should be built.

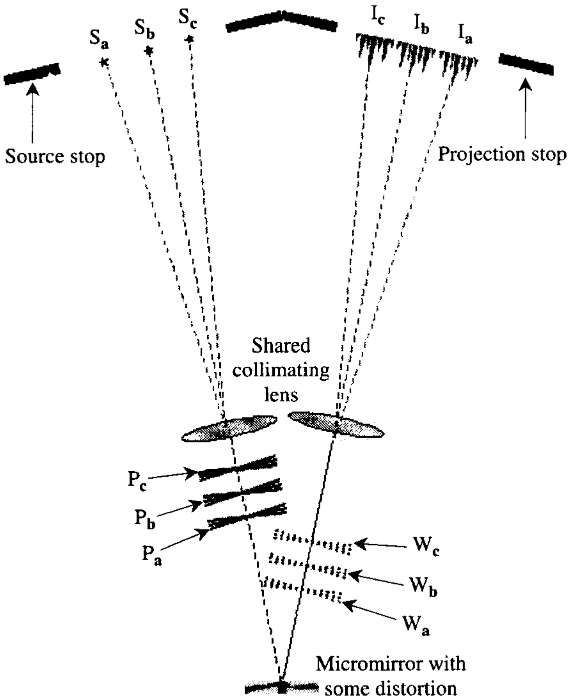

Fig. 6 Processes of simulation

4.2 Simulated and Real Image

The micromirrors which are lately being manufactured have a tilt of 0° ~ 0.2° from the initial condition that no driving voltage is applied to the actuating PZT layers. So, all the micromirrors with initial tilt angles need to be calibrated to use them as effective spatial light modulators. Since measurement data also contain a initial tilt angle, a process of calibration is necessary. For effective simulations, the reference plane of a surface profile is found by the least square method and the surface profile is so rotated as for the reference plane to be leveled. Fig. 7 displays both the surface profile of a micromirror and its reference plane.

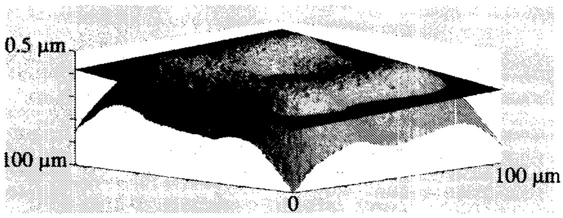

Fig. 7 Surface profile of the measured micromirror and its reference plane by least square method

With the information of heights from the measurement data of a certain micromirror, the image of the broad source was obtained through the proposed process of simulation. Fig. 8(a) is the estimated image of the broad source when the driving tilt angle of the measured micromirror is 3 degrees. Fig. 8(b) shows the real slantwise image at the projection-stop plane when a TMA™ chip is set up in the TMA™ projection system. The real image is fairly similar to the simulated image where the bright center part with ambiguous edges has four arms upward, downward, right and left.

There are two significantly different meanings between the two images. The simulated image is obtained by a monochromatic light and only one micromirror but the real image is created by the white light with many frequencies and many micromirrors in the mirror chip. The latter of the two means that the images by one micromirror and by many micromirrors are not identical, because, in terms of wave optics, transmittance function becomes changed if only the geometrical values such as shapes, sizes or numbers of micromirrors are changed.(9) Keeping within the limits of geometrical optics for understanding the difference more easily, the real image could be considered to be the superposition of images created by each micromirror with different initial tilt angles.

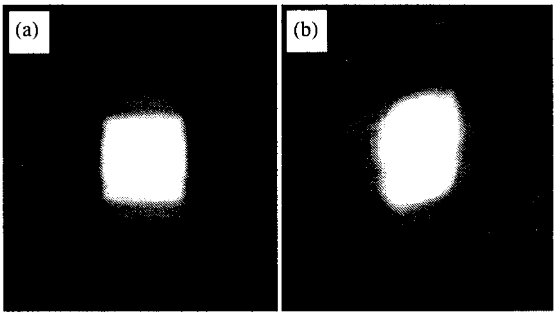

Fig. 8 (a) Estimated image and (b) real image of the broad source at the projection-stop plane

4.3 Estimated and Experimental Results

If the proposed method of analysis is made use of as it is, the images at the projection-stop plane can be acquired according to any driving tilt angles ranging from 3 degrees to 0 degree. And, if only the intensity distribution of the total image is gained, the amount of light passing through the projection stop can be calculated, considering the position and size of the projection stop. The line (a) of Fig. 9 shows in percent the ratio of the amount of thru light to the total light reflected by a micromirror as the driving tilt angle decrease from 3 degrees down to 0 degree. The curve could be called the "gray-scale line" of the measured micromirror. Especially, the gray-scale value at 3 degrees means the optical efficiency which the micromirror has with regard to the mirror flatness. As it is shown in the gray-scale line, it is characteristic of non-linearity in its first and last part, because, particularly at the edges of the blurred image, the increase or decrease of the amount of thru light is not constant though the blurred image moves by a constant distance.

To verify the estimated gray-scale lines, the optical system as in Fig. 10 was set up. The experimental setup utilizes a beam splitter instead of the source mirror, which is used in the TMA™ projector, and the color filter, which makes the light from the halogen lamp quasi-monochromatic. The line (b) of Fig. 9 is the experimental values that can be compared with the simulated values of the line (a). The experimental gray-scale line is not very smooth due to the non-uniformity of pixel sensitivity of the CCD and the instability of the light source but it shows a overall tendency and feature similar to the simulated gray-scale line. There could be many causes of errors explaining the difference between the two lines, but there are two noteworthy ones. They are about the number of wavelengths and micromirrors just as they existed between the estimated image and the real one discussed above. Therefore, when more rigorous analyses and experiments are essential, the condition that the two transmittance functions should be equal is necessarily required. That is, multiple micromirrors have to be measured for a comparable analysis, or the experiments should be carried out with only a single micromirror placed on the mirror chip.

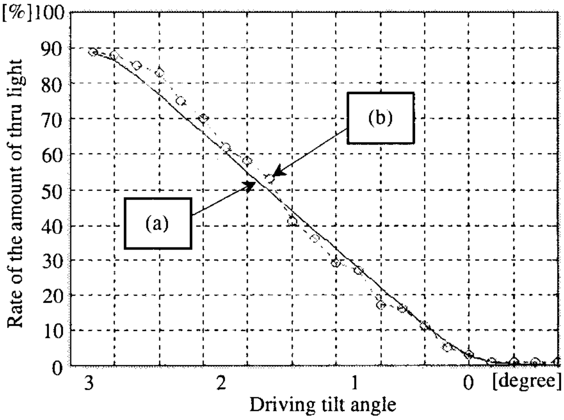

Fig. 9 Comparison between (a) the simulated gray-scale line and (b) the experimental gray-scale line

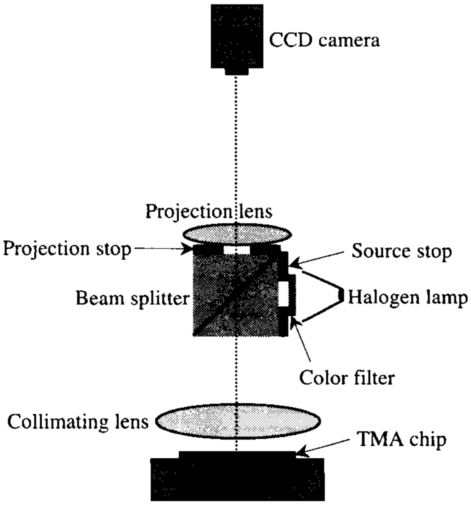

Fig. 10 Schematic diagram of the experimental setup

4.4 Change of Peak-to-Valley Value

Micromirrors on a TMA™ chip are manufactured by semiconductor processes and peak-to-valley (PV) values of the micromirrors increase or decrease, depending upon manufacturing processes. Micromirrors with increased PV values cause the image of the broad source to be blurred and the optical performance of the projection system is expected to fall. As the PV value of the surface profile of a micromirror with a typical shape of distortion among the ones in a TMA™ chip changes, how its optical efficiency and its gray-scale line undergo changes was investigated. Fig. 11 shows the rate of the amounts of thru light as a surface in three dimensional space according to the changes of driving tilt angles and PV values. The surface could be named the "surface of thru light," which is composed of a "line of optical efficiency" and "gray-scale lines" in a sense. Since the gray scale reaches its maximum when the tilt angle is 3 degrees, the curve connecting the maximum values, which are related to each PV value, could be called the "line of optical efficiency." With a PV value fixed, the curves according to the driving tilt angles could be called the "gray-scale lines."

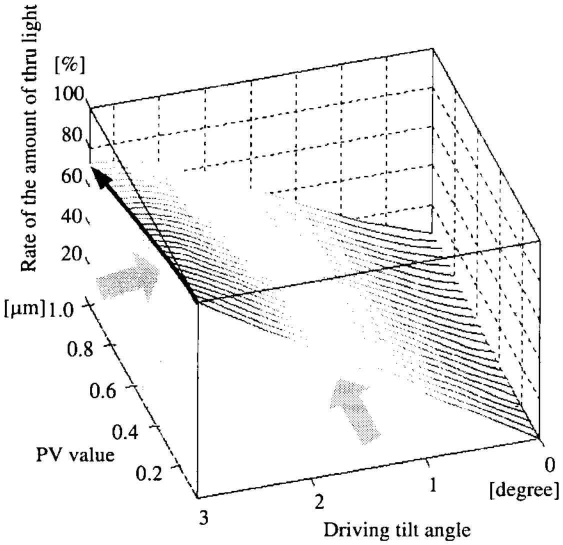

Fig. 11 Surface of thru light

The front view of Fig. 11 is Fig. 12, where non-linearities emerge gradually conspicuous in their first and last parts as the PV value of the measured micromirror increases. The increase of non-linearity means the loss of optical efficiency and the decline of contrast ratio.

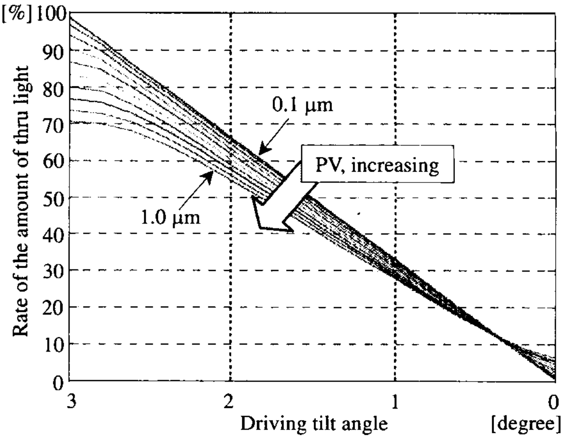

Fig. 12 Changes of the gray-scale line

5. Conclusions

Under the optical structure of the TMA™ projector, the shape of image at its projection-stop plane has great influence on its optical performance. Accordingly in this study was investigated how much influence the form errors of a micromirror surface exert on the optical efficiency and the modulation of gray scale of the TMA™ projector.

Taking into account the single wavelength and the single micromirror used in the simulation, the estimated image was fairly similar to the real one at the projection-stop plane. Concerning the estimated and experimental results for gray-scale line, both had the same feature of non-linearity in their first and last parts, although there was somewhat difference between them due to the different number of wavelengths and micromirrors.

These consequences support that the method proposed in this study is quite useful in the optical interpretations of micromirrors, so that we can predict by the very analytical method the change of gray-scale value as well as the optical efficiency which the TMA™ micromirror of interest have. Also, the method is able to be applied to any other shapes of micromirrors successfully as well as the current square shape of TMA™ micromirrors. Furthermore, if necessary, it is applicable to the optical analysis of micromirrors in MOEMS (Micro-opto-electro-mechanical Systems) specially with the form of spatial filtering at its Fourier plane.

In addition, the change of both the optical efficiency and the gray-scale line were looked into as the PV value of the surface profile of the measured micromirror changes. According to changes of its PV value and its driving tilt angle, what is called the "surface of thru light" was able to be obtained. From the very surface, both the amounts of loss of the optical efficiency at each PV value and the change of gray-scale value at an arbitrary driving tilt angle can be known with ease. And it was verified by the very surface that non-linearity increases at the first and last parts of the gray-scale lines as PV value increases.

Because the increase of non-linearity drops contrast ratio on screen, as low PV values of micromirrors as possible are essential. And besides, since contrast ratio falls because of the diffraction by spatial frequencies of the multiple micromirrors as well, another way of modulation of thru light is supposed to be necessary in order to greatly enhance the image quality of the TMA™ projector.

Acknowledgement

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