Optical scanners for high resolution RSD systems

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ABSTRACT

This paper outlines the design trade-offs and measured results of scanner architectures for use in high resolution Retinal Scanning Displays: Mechanical resonant for horizontal scanning, and MEMS-based pinch correction and vertical linear scanners. Analysis steps and techniques used to model and minimize dynamic deformations are covered. This paper also discusses two types of scanners and associated mirror flatness issues. Dynamic flatness modeling and performance results are presented, followed by thermally induced deformations and possible athermalize solutions for MEMS-type scanning mirrors. Theory, FEA dynamic and thermal analysis, experimental results, and methods to reduce mirror deformation are discussed.

Keywords: MEMS Scanners, raster pinch correction, mirror deformation, electromagnetic actuators

1. INTRODUCTION

Retinal Scanning Display (RSD) operation and system architecture is discussed in detail elsewhere.^{1,2,3} RSDs typically employ two uniaxial or one biaxial scanner where the horizontal scanner is operated at resonance, and the vertical scanner is driven by a sawtooth waveform^{4,5}. The combined motions of the two scanners create a 2-D sinusoidal raster. A third scanner, referred to as the raster pinch correction scanner (RCS), with very small scan angle can be added to the system to correct for non-uniform line-to-line spacing of the resulting sinusoidal raster.

This paper has two main parts. The first part discusses the dynamic mirror flatness due to high strain and acceleration forces for mechanical resonant scanners (MRS). The second part discusses mirror flatness due to a thermal load for a MEMS-based RCS.

2. MRS OPERATION

A mechanical resonant scanner, illustrated in Figure 1, is actuated using two electromagnets and operates in a resonant mode. Permanent magnets, U-core, scan mirror, and the base plate are all part of the magnetic circuit. The scan mirror has high magnetic permeability and the magnets at the end points of the torsion arm create a magnetic flux through the gaps on both ends between the mirror plate and the U-core. The constant DC flux creates a downward force on either end of the mirror plate and pulls the mirror down; but the net torque or twisting moment is zero. When opposing currents flow through the coils, the force is no longer balanced and the mirror starts to tilt in response to the current. Where the currents are AC, the mirror pivots periodically and can act as a scanner.

Resonant scan mirror mechanical design and tradeoffs were discussed in Ref. 6. As described in Ref. 6, display system resolution is determined primarily by the scan-mirror-size and scan-angle product, and the number of display lines is primarily determined by the scanner frequency. Mirror and flexure dimensions should be selected such that the design meets the specified resolution, resonant frequency, mirror deformation, stress on flexures, and optical requirements.

Another design variable is the mirror material. The material for the MRS should produce high optical quality mirrors when polished. Moreover, it should have high magnetic saturation point and high permeability for drive efficiency. Additionally, the flexures should have a high yield stress. A number of materials have been examined and a type of Carbon steel was selected as the best mirror material.

Figure 2 shows the mode frequencies and shapes obtained using finite element analysis (FEA) of the MRS structure. For the design in the figure, the torsional mode is the third Eigenmode. To prevent energy coupling to other oscillation modes, other mode frequencies should not be close to the torsional mode frequency and its harmonics.

Figure 1: Mechanical resonant scanner (MRS) structure

3. MRS DYNAMIC DEFORMATION

Both static flatness and dynamic flatness of the scanning mirror are important for image quality. Even a very small amount of deviation from linearity due to mechanical deformation can result in optical distortion of the pixel and the image. Large acceleration forces during mechanical deflection of the mirror produce mirror deformation and the maximum deformation occurs at the extremities of the scan. For rectangular block mirrors, 1-D theory can be used to derive the following formulas for the maximum mirror deformation and the deviation from linearity as a function of mirror position⁷:

$$\delta(u) = \delta_{\max} (u^5 - 10u^3 + 20u^2 - 11u) / 1.83 \quad (1)$$

$$\delta_{\max} = 0.217 \frac{\rho f^2 D^5 \theta_{MMSA}}{Et_m^2} \quad (2)$$

u = normalized mirror surface coordinate perpendicular to rotation axis

ρ = material density

E = modulus of elasticity (Young's modulus)

f = scanner frequency

θ_{MMSA} = 0-peak maximum mechanical scan angle

Figure 3(b) shows the mirror surface shape as a function of u ($u = \pm 1$ correspond to edges of the mirror). As seen from the figure, the deformation is symmetrical with respect to the center of the mirror. For the kind of aberration the mirror introduces, the maximum mirror deformation ($\delta_{\max}$) should not exceed $\lambda/10$ of the shortest system wavelength for the spot to remain diffraction limited across the scan line. Note that $\delta_{\max}$ is proportional to $D^5 \theta$. If system performance is deformation limited, significant gains can be attained by slightly reducing the mirror size.

Figure 2: MRS mode shapes and frequencies for the design illustrated in Figure 1.

Figure 3: (a) Dynamic mirror deformation graphical representation, (b) surface profile as a result of deformation at maximum scan angle and at half maximum scan angle. Maximum deviation from linearity attained at about 40% of the way from center to the edge of the scanner. MMSA: Maximum mechanical scan angle (0-to-peak).

The formulas above are derived using the beam deflection theory under a distributed acceleration force. Theoretical formulas are valid only for the 2-D mirror geometry shown in Figure 3(a), where the mirror length (mirror dimension along the flexures) and the flexure joint area are assumed to be small. In reality, the length of the MRS mirror is nearly equal to its width and the flexure joint area is made even larger than the nominal flexure cross-sectional area. A bevel is introduced at the flexure joints to reduce the scanner breakage due to large stresses at large deflections. Thus, validity of the theoretical formulas is limited and FEA should be used for predicting deformation for 3-D mirror geometries.

Figure 4 shows the dynamic deformation predictions for the previous MRS, which had large amount of mirror deformation. Note that the strain induced on the mirror plate by the flexures causes a large amount of deformation around the flexure joint points. Also note that the corners of the mirror deflect up and down more than the rest of the mirror and introduce a large amount of optical aberration. Mirror deformation can be reduced by making the mirror thicker, by cutting the corners of the mirror, by changing the shape of the flexure joint points, or by illuminating only the central portion of the scanner. Before making a change, one needs to consider the impact on the other important scanner performance metrics. Thicker mirrors reduce the deformation; however, they also result in larger inertia, requiring larger drive torque and stiffer flexures to meet the resonant frequency requirements. Cutting the corners reduces the inertia and the mirror deformation; however, it also reduces the torque coupling from magnets to the mirror and the size of the torque arm, requiring actuator redesign. Alternatively, one can avoid illuminating the corners by using an elliptical aperture before the scan mirror. Flexure joint points are typically stress concentration points. Removing the bevel can reduce the strain on the mirror, but increases the stress on the flexure, limiting the maximum scan angle.

We have gone through several iterations in optimizing the actuator and the mirror design. The mirror design illustrated in Figure 5 has good optical, mechanical, and magnetic properties. There are several key changes incorporated into the new MRS design. Magnetic torque coupling for elliptical and rectangular mirrors have been evaluated and the drive power requirements with optimized magnetic actuators in each case were found to be about the same. Elliptical mirror is the preferred configuration as it results in smaller mirror deformation. The most important change that was made to the structure is the cut that was introduced underneath the mirror. The undercut allowed decoupling the mirror plate from the flexures, eliminating the strain induced on the mirror. As seen in Figure 6, these modifications substantially reduced the mirror deformation. Overall thickness of the new MRS design is larger than the thickness of the old MRS, however, the mirror inertia and the frequency remained about the same. In addition, the new MRS design did not change the torque coupling into the scanner significantly. The new MRS design made the pixels essentially diffraction limited (i.e., further reductions in the mirror deformation would not improve the pixel resolvability or the system modulation transfer function (MTF) any more). The new MRS design increased the number of resolvable pixels across the scan line quite significantly.

Figure 7 shows the experimental dynamic deformation measurements using a Shack-Hartmann wavefront sensor and a diode light source that produces short pulses at the operation frequency of the scanner. The timing of the pulse within the scan cycle is adjusted using a delay pulse generator.⁸ The experimental deformation figures were consistently lower than FEA predictions by about 10% to 20% in different designs. We consider this good agreement between the model and the actual device performance. This much discrepancy is typically expected and can be attributed to the variation in material properties during operation. Once the material properties are modified in the model, the variation between the model and the actual performance becomes less than 10%, which indicates that our FEA model is indeed a very good one.

FEA PREDICTION ESK1B @ 16.8 KHz, 4.5 DEGREE DEFLECTION
 RESULTANT SURFACE IN WAVE LENGTHS OF LIGHT (532 nm) OVER 4 X 3 MM USEABLE AREA

Figure 4: FEA dynamic deformation results for old MRS 16.8 KHz and 4.5° mechanical scan angle.

Figure 5: New MRS mirror structure

HESK1 (SXGA 4.4 MM ELLIPTICAL MIRROR, 16.8 KHz)
RESULTANT SURFACE IN WAVE LENGTHS OF LIGHT (532 nm) OVER 4 X 3 MM USEABLE
AREA

Figure 6: FEA dynamic deformation results for new MRS: 16.8 KHz and 4.5° mechanical scan angle.

Figure 7: Experimental deformation results for old and new MRS: 16.2 KHz and 4.5° mechanical scan angle.

4. RASTER-PINCH CORRECTION (RCS) SCANNER OPERATION

Bidirectional scanning refers to writing a line of data during both forward and backward sweeps of the resonant horizontal scanner. Bidirectional scanning improves the light efficiency and the line rate of the display system, but results in non-uniform line spacing for points away from the center of the screen. Non-uniform line spacing or the raster pinch problem can be corrected by adding a third scanner to the system, called the raster pinch correction scanner or RCS^{9,10,11}.

A preferred actuation mechanism for the RCS is the moving coil electromagnetic actuator and the torsional scan mirror depicted in Figure 8. Same scanner architecture and actuation mechanism can also be used for vertical scanner implementation. MEMS technology is well suited for fabricating a number of design variations on the same batch and for depositing micromachined coils attached to the scanner. The mirror is etched on Silicon using deep reactive ion etching (DRIE) to tightly control the flexure and mirror dimensions. The magnets in the figure produce a static magnetic field across the gap. The cross product of the magnetic field along the horizontal axis and the current along the vertical axis produces a force perpendicular to the page. The opposite current direction on different sides of the coil generates forces into and out of the page, resulting in a net torque or twisting moment on the torsional scan mirror.

The RCS operates at exactly twice the frequency of the resonant horizontal scanner and the required scan angle is less than half of the angular width of a single pixel. In an SXGA resolution two-line bidirectional RSD implementation, this requirement corresponds to about 5x5mm mirror operating around 32KHz and at $\pm 2\text{mdeg}$ mechanical scan angle. The RCS is slaved to resonant horizontal scanner. For good controllability, RCS resonant frequency should be sufficiently far from its operation frequency. Another important requirement is that, since the scanner is used in a military system, the product should be designed to operate in the range -20°C to $+50^{\circ}\text{C}$. RCS performance requirements and current performance levels have been studied in detail and published elsewhere^{10,11}.

Figure 8: Torsional raster pinch scanner (a) front and back sides, (b) coils and magnets for the moving-coil-actuation.

5. THERMAL MODELING

Changes in the ambient temperature and the power dissipated at the coils during operation introduce a thermal load on the mirror. Due to Coefficient of Thermal Expansion (CTE) mismatches of the materials in the assembly, thermal load can cause temperature differentials and mirror deformation. Temperature differentials will be relatively small due to high thermal conductivity of silicon so the deformations due to temperature effects will be primarily caused by the CTE mismatch. Designing the operational temperature to be close to the zero stress temperature of the assembly can minimize bending due to CTE mismatch. This bending can be reduced by increasing the stiffness of the mirror relative to the stiffness of the coils.

Figure 9 shows the experimental verification of the linear power relationship. The data were taken at room temperature using a thermocouple. Using the slope of the figure, the temperature rise coefficient is calculated as 0.190°C/mW . Table 1 shows the CTE value for the materials used in the calculations.

Table 1: Coefficient of thermal expansion for Si and various materials.

CTE Silicon	$2.6 \text{ e-}6 \text{ m/m/}^{\circ}\text{C}$
CTE Gold	$14.0 \text{ e-}6 \text{ m/m/}^{\circ}\text{C}$
CTE Copper	$16.9 \text{ e-}6 \text{ m/m/}^{\circ}\text{C}$
CTE Aluminum	$24.0 \text{ e-}6 \text{ m/m/}^{\circ}\text{C}$

Figure 9: Experimental results for temperature rise as a function of dissipated power on the coils.

Figure 10: FEA results for mirror deformation as a function of coil thickness for 300 μm and 600 μm thick Si wafers. The mirror metal is 2 μm Al.

Figure 10 shows the thermally induced peak mirror deformation as a function of coil thickness assuming the temperature of the device increases by 25⁰C, corresponding to about 120mW dissipated power at the coils. Using FEA, we determined that the thermal deformation is proportional to the metal coil thickness and inversely proportional to the square of the silicon wafer thickness. Zero deformation is obtained at a non-zero coil thickness due to 2 μm Aluminum mirror plated on the opposite side of the wafer.

If a Silicon wafer is sandwiched between two materials where both have higher or both have lower CTE compared to Silicon, then the thermal stress on each surface has opposing directions, reducing the resultant thermal deformation. If the thickness (t) of the mirror metal and the coil are chosen such that it satisfies the below criteria, then the thermal deformation can be completely eliminated, making the scanner athermalized:

$$\frac{t_{\text{mirror}}}{t_{\text{coil}}} = \frac{CTE_{\text{coil}}}{CTE_{\text{mirror}}} \frac{A_{\text{coil}}}{A_{\text{mirror}}} \frac{E_{\text{coil}}}{E_{\text{mirror}}} \quad (3)$$

where coil and mirror subscripts refer to coil and mirror materials (bottom and top surface metals in Figure 8), A is the fraction of the surface area covered by the metal, and E is the Young's modulus. This relationship is verified by FEA.

Figure 11 illustrates the mirror deformation for a 300 μ m Silicon die with 6 μ m gold plated on one side and an Aluminum mirror plated on the other side of the wafer. Al thicknesses in two cases illustrated in the figure are 1 μ m and 2 μ m. Note that the corners of the mirrors are bent down when no power is applied and the mirror becomes nearly flat when about 100mW is applied to the mirror, then the corners start to bend up at larger power levels. When the mirror has the best flatness (when power dissipated is around 100mW), the mirror temperature reaches to the Al deposition temperature, which gives zero stress. Any remaining mirror deformation at that point is due to fabrication, not due to thermal stresses. Increasing the Al thickness from 1 μ m to 2 μ m reduced the thermal deformation significantly. The Al thickness required to completely athermalize the structure could be calculated using the above equation.

Figure 11: Interferometrically measured mirror flatness for two scanners with different mirror thickness. Top three figures are obtained for 1 μ m Al mirror case; bottom three figures are obtained for 2 μ m Al mirror case. All graphs have the same scale.

6. SUMMARY

Mirror deformation due to large acceleration forces and strain induced by the flexures can be reduced by various structural enhancements without changing the mirror size and mass significantly. The biggest improvements are obtained by decoupling the mirror plate from the flexure joints by introducing a cut underneath the mirror and by making the mirror shape elliptical rather than rectangular. FEA predictions and experimental results are in good agreements. We also investigated the scan mirror deformation due to ambient temperature changes and due to power dissipated at the actuator coils that are attached to the scan mirror. Using FEA and experimental results, we developed empirical formulas to predict mirror deformation and scanner temperature. If the mirror is sandwiched between two materials (e.g., mirror metal

and coil metal), then the thermal stresses due to each metal can be balanced by choosing appropriate thickness for the metals on either side of the mirror, making it possible to completely eliminate the thermal deformation.

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