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# Design Considerations for Fast Steering Mirrors (FSM's)

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## ABSTRACT:

The single-axis and two-axis, flexure mounted, fast steering mirror (FSM) represents a compact, low cost, high performance design solution for a variety of emerging optical scanning and beam stabilization applications. Such devices are used to correct for polygon cross scan errors in prepress photography, acquire and lock beams within free space laser telecom systems, modulate tilt and cavity control in interferometers, maintain beam stabilization in the presence of thermal drift and vibration, and provide general two axis beam scanning. This paper discusses the tradeoffs among range of motion, spring selection, actuator types, mirror designs, and control systems. Actual product design and performance data is presented for a single axis FSM used for polygon cross scan error correction, and a dual axis FSM used for free space laser telecom.

**Keywords:** FSM, flexure, virtual pivot, PZT, voice coil actuator, metal mirrors, servo, DSP, linearity, hysteresis

## INTRODUCTION:

For the purposes of the discussion to follow, a fast steering mirror (FSM) is defined as a mirror mounted to a flexure support system that may be moved independent of the natural frequency of the spring/mass system to direct a laser beam or other light source. A flexure or combination of flexures sustains means of support for the mirror and allocates compliance and constraint of motion among the six degrees of freedom. The exceptional elastic repeatability of flexures is also exploited in typical applications. Actuators such as voice coils and piezoelectric devices are commonly used to apply precisely metered motion in the compliant directions. In most cases, a feedback control system that senses errors in the trajectory or phase of the reflected beam is used to fine tune the position of the mirror.

## DISCUSSION:

Three different flexure mounted mirror cases are shown in the figures below:

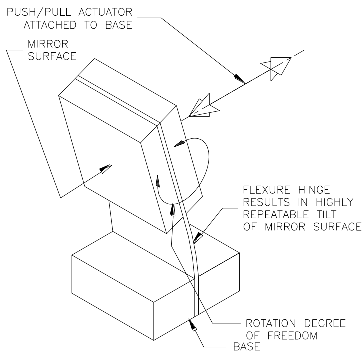

Figure 1a: Fast, single axis tilting mirror

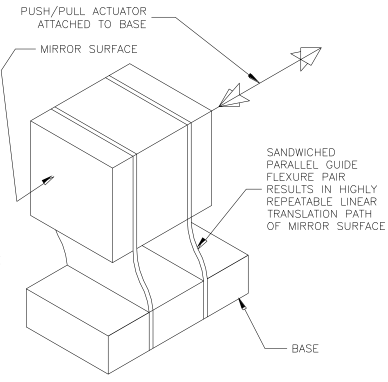

Figure 1b: Fast, single axis translationg mirror

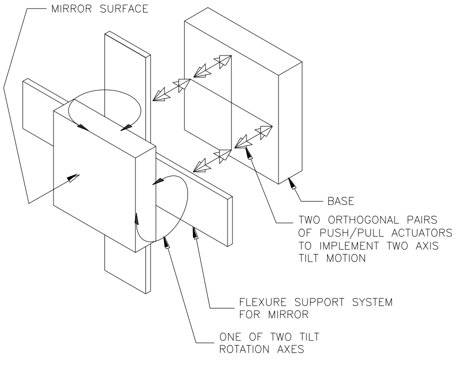

Figure 1c: Fast, two axis tilting mirror

In the first case (fig. 1a), a flexure is used as a single axis hinge to allow only tilt in one direction. Two such devices can be used in tandem to provide two orthogonal axes of tilt in a scanning or beam stabilization mode. If the beam is collimated, the resultant translation of the mirror in addition to tilt is not a significant issue. The inherent simplicity of this design along with its exceptional elastic repeatability is key to the polygon cross scan correction FSM discussed below. In the second case (fig. 1b), two flexures are used to allow only translation along the axis of the mirror. This type of design can be used to rapidly modulate an interferometer cavity for FFT waveform analysis. In the third case (fig. 1c), a mirror is mounted to a two-axis flexure system with a center pivot flexure that allows only two axes of tilt adjustment. This type of design is ideal for a number of beam stabilization and scanning applications including the case of a free space laser telecom system discussed below. There is a wide variety of ways the basic concepts illustrated in figures 1a,b,c may be embodied in real life designs subject to application specific requirements for range of motion, mirror aperture, mirror flatness, dynamic response, etc.

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## Range and Type of Motion:

The required range and type of motion is a critical consideration in the design of flexure mounted mirrors. Generally flexures can only be used over a limited range of motion compared to linear or rotary bearings, although extended ranges of motion can be achieved by reducing flexure spring rate and innovative actuator interfaces.

An additional consideration is the selection of actuator type and how it is attached to the moving and fixed portions of the support structure. The relationship of the actuator(s) to the virtual pivot of the flexure system is vital to achieving optimal actuator response and optimizing the range and fluidity of motion.

## Flexure Spring Design:

Spring design and material selection is also a vital criteria in the design of flexure mounted FSM's. Spring rate in both the compliant and non-compliant directions must be considered simultaneously. An ideal FSM flexure system would have the following attributes:

- Very low stiffness to resist the desired directions of motion
- Very high stiffness in the constrained directions of motion
- Controlled location of virtual pivot of flexure system
- Near-perfect elastic response in the desired directions of motion
- Low mechanical hysteresis
- Very high resistance to metal creep and fatigue
- Compatible coefficient of thermal expansion with the mirror and its mount

A wide selection of spring materials, spring types and associated manufacturing technologies are available for flexure supported FSM designs. Beryllium copper and other spring materials are well suited as flexures and may be formed in a wide variety of shapes when cut or stamped from varying thickness of commercially available sheet stock. Integrally machined flexures in mirrors fabricated from aluminum or beryllium are also feasible so long as metal fatigue thresholds are not approached and features having high stress concentration factors are avoided.

Generally attempts are made to conserve energy, and reduce actuator force requirements by minimizing the spring rate of the flexure in the compliant directions. This minimizes the holding force that the actuator must express to maintain the mirror at a commanded position against the resistance of the flexure. Conversely, it is desirable to maintain very high spring rates for constrained degrees of freedom. These principles can be seen in the three flexure supported mirror diagrams shown in figures 1a,b,c above. For each case, the mirror will move readily in the desired directions but is resistant to motion in the constrained directions. The appropriate balance of spring rate and range of motion for all of the six degrees of freedom must be accommodated in the flexure design process.

An additional consideration is the virtual pivot of the flexure design. All flexure designs have a virtual pivot point, axis, or surface. In many cases it is desirable to locate the virtual pivot at the plane of the mirror surface.

## Actuator Choices:

Voice coil and piezoelectric (PZT) type actuators are commonly used to operate flexure supported FSMs. Voice coils consist of a coil of wire and a permanent magnet. By modulating the amplitude, frequency and direction of the current flowing through the coil, a precisely metered push or pull effect can be realized. The coil and magnet must be guided by bearings or the flexure design to maintain alignment over the range of travel. Generally the efficiency of the voice coil degrades as the clearance between the coil and the magnet is increased. Voice coil actuators have the advantages of large travel excursion, moderate frequency response and the potential for finely metered increments of motion. Voice coils can also be designed such that the coil and magnet are curved about a virtual pivot point or axis. In this manner expanded ranges of tilt can be achieved. Voice coils can also produce an impressive amount of force in a small package.

PZTs typically consist of laminated stacks of piezoelectric material encased in a steel cylinder. By application of a modulated high voltage signal to the PZT, small increments of motion result. When compared to voice coils, PZT actuators can produce tremendous force in a smaller package at much greater frequency response. However, PZTs suffer from very limited range of travel, hysteresis, and they must be mechanically preloaded in compression to prevent de-lamination and to provide a restorative spring force.

A combination of high frequency, high load, and small tilts or translations favors the use of a PZT to actuate the FSM. Large ranges of excursion and low load favor the voice coil actuator.

## Mirror Design issues:

The opto-mechanical engineer is faced with the challenge of developing a mirror design that compromises neither the mechanical requirements nor the optical requirements of a given FSM application. The optical requirements are generally expressed in terms of aperture size and wavefront error. The aperture size is a function of the size of the beam that must be directed plus a reasonable allowance for mirror manufacture (such as edge roll-off) and misalignment error stack-ups within the entire product. The wavefront error tolerance relates to degradation of the beam due to imperfections in the surface flatness of the mirror under both static and dynamic conditions.

Although it is tempting to make the mirror oversized in thickness and aperture to eliminate worry about meeting the optical requirements, the additions to mass and moments of inertia run counter to the goals for the actuator design and the associated control system. In such cases, a sufficient design for the mirror can be determined by finite element analysis (FEA). Glass or metal mirrors may be used in the FSM design. Glass mirrors are inexpensive and can be very high quality but lack the design versatility of metal mirrors. In many cases the use of mirror materials having exceptional stiffness/mass ratio such as beryllium or silicon carbide can be used. These materials have a specific stiffness (Young's modulus/density) that is 4-6 times greater than common optical glass materials such as BK7 and fused silica and common structural metals such as aluminum, magnesium, steel, and titanium.

Mounting of the mirror to the flexure support system is also extremely critical. Use of a glass mirror typically requires the use of an adhesive at the back or sides of the mirror for attachment to a metal structure that is then attached to the flexure and actuator system. Dissimilar coefficients of expansion among mirror and support materials can result in mirror figure distortion upon changes in temperature. The use of adhesives often result in dimensional creep and reduction in the natural frequency of the suspended mirror system. Metal mirrors are readily designed for direct (no adhesives) fastening to the flexure and actuator system. The metal mirror may also be designed with integrally machined flexures, light-weighting to increase the structural efficiency and other features not attainable with glass mirrors. For particularly demanding FSM applications, metal mirrors can yield significant performance advantages over glass mirrors.

**Control Systems:**

Typically FSMs are used in the context of a closed loop feedback servo control system. A sensor or sensing system identifies errors in the trajectory or phase of the light beam and reports the error back to the control system, that, in turn commands the actuators on the FSM until the error is reduced to tolerable limits. The repeatability of the flexure is often exploited and a profile of the elastic response can be stored and replayed in open loop mode to reduce the dynamic range of closed loop error correction. This technique is used in the actual single axis FSM device discussed below.

## FSM Example #1: Single Axis FSM for Polygon Cross Scan error Correction:

The following application describes a single axis FSM used to correct for cross scan error introduced by a rotating polygon in the context of a flat field photographic print engine. This product is used to expose “computer to plate” (CTP) materials used in offset printing. The FSM is required to compensate for tilt errors on the order of 0.10 arc-second at rates of 20 kHz. The FSM must also compensate for small errors in the flatness of the polygon facets since minute twists in one facet relative to the next facet result in beam trajectory errors and undesirable “banding” artifacts in the photographic copy.

In this case the small angular range of motion and extreme stiffness and repeatability required suggests the use of small single axis flexure mounted mirror. By use of a metal mirror, it was also possible to integrally machine the flexures into the mirror substrate. The small range of motion and high frequency response favored the selection of a piezoelectric (PZT) type linear actuator. The selection of a metal mirror substrate also allowed the mirror to be hard mounted directly to the tip of the PZT. Peak accelerations are in excess of 200 g’s. In the final result an extremely responsive, compact, and reliable FSM module was developed with an exceptionally repeatable tilting motion about a virtual hinge axis defined by two integrally machined pivot flexures.

The rotating polygon is mounted on an extremely accurate self-acting air bearing motor system. Variation in the flatness of the facets and gross cross scan errors for each scan rate are calibrated at the factory for several points in the scan for each facet and stored in memory to govern modulation of the PZT in synchrony with the rotation index of the polygon. A position control system known as “cross scan update (CSU)” senses scan line to scan line errors at the beginning of scan as subtle departures from the factory error map develop. “On the fly” corrections are then summed into the control of the FSM along with the factory error map profile until the errors are reduced to tolerable levels. The extraordinary short-term repeatability of the air bearing scanner platform permits averaging of many scanner revolutions prior to calculating and inserting a bias correction to the factory error map. The repeatable elastic response of the flexure hinge integrally machined into the FSM over billions of cycles is also critical the success of the system.

A general summary for the polygon correction FSM is as follows and is illustrated in figure 2:

- Type: Single axis flexure
- Mirror: Diamond machined metal with integrally machined flexures
- Actuator: PZT
- Peak tilt: +/-30 arc seconds mechanical
- Scan Frequency: 1600 Hz
- Incremental correction frequency: 20 KHz
- Clear aperture: 3 mm 1/e2
- MTBF: Over 50 E010 cycles (1600 Hz, 3000 hours/year, 3 years)
- Control System: type 1 servo (zero static error for a constant output displacement)

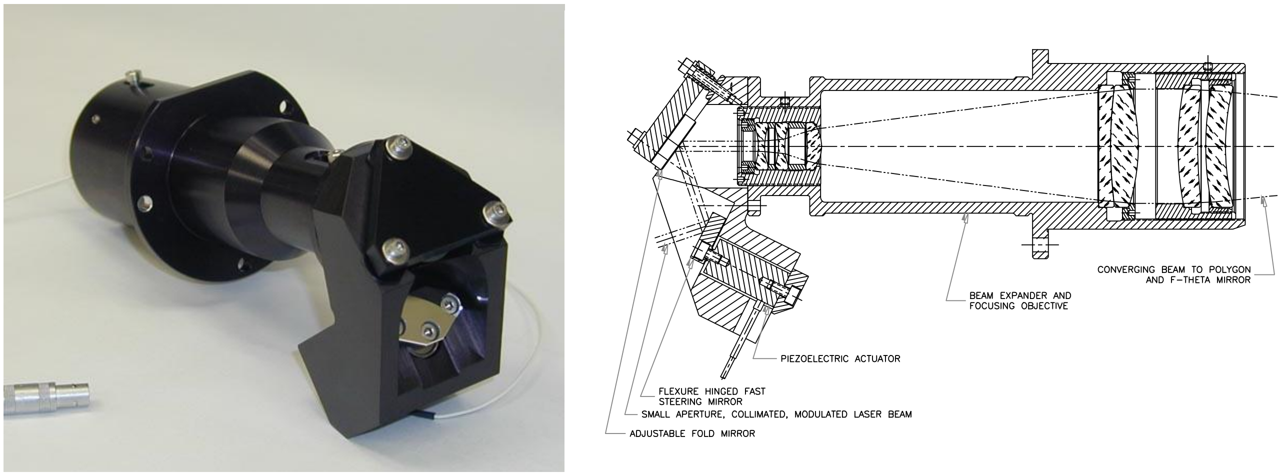


Figure 2: Photo and sectional view of single axis FSM mounted in laser conditioning/focusing objective.

## FSM Example #2: Two Axis FSM for Free Space Laser Telecom:

Free space laser telecommunication systems entail propagation of modulated laser signals across open atmosphere or the vacuum of space rather than through fiber optic cable. In effect, identical bandwidth compared to fiber cable transmission, at the same laser wavelength, can be achieved. Demanding requirements for acquisition scanning and signal lock in such systems have turned renewed attention to flexure suspended fast steering mirrors. The requirements for low cost and moderate angles of excursion suggests the use of a two axis flexure supported FSM driven by voice coil actuators. A picture of a two axis tilt FSM and a schematic of a laser telecom link are shown in figures 3, 4. A common path laser emitter and receiver are positioned opposite each other, often at large separation distances. The FSM within each module compensates for any environmental disturbance that results in a shift in the optimal co-alignment of the two systems.

Since the dynamic response characteristics were not particularly demanding, a sufficient design was developed without the use of exotic mirror materials, light-weighting of the mirror, or ultra-high performance actuators. Systematic engineering analysis resulted in a spring suspension system that was maintained exceptionally stiff in three axes of translation and one axis of rotation. The remaining two degrees of freedom, reserved for tilt of the mirror surface, were designed to have a very low spring rate and were essentially uncoupled from one another. The virtual pivot of rotation was maintained as close to the center of the mirror aperture as was possible. Two pairs of voice coils, operating in push/pull manner for each tilt axis, act directly upon the mirror mount and are suspended with the mirror on the flexure system. The voice coil magnets are fixed mounted to the base of the FSM. By maintaining very low, yet highly elastic spring rate in the desired compliant directions, the energy required to hold the mirror at a given location for extended periods of time is not excessive. By balancing the mirror, its mount and the actuator coils such that the center of gravity of the mirror coincides with the virtual pivot of tilt, the FSM may be mounted in universal orientations without significant change in mirror angle relative to reference datums.

A general summary for the two-axis FSM is as follows:

- Type: two axis flexure
- Mirror type: Diamond machined metal with integral hard fastening
- Actuator: Linear voice coil
- Peak tilt: +/-3 degrees mechanical
- Clear aperture: 35 mm
- Bandwidth requirements: 500-1000Hz
- Control System: type 2 position servo

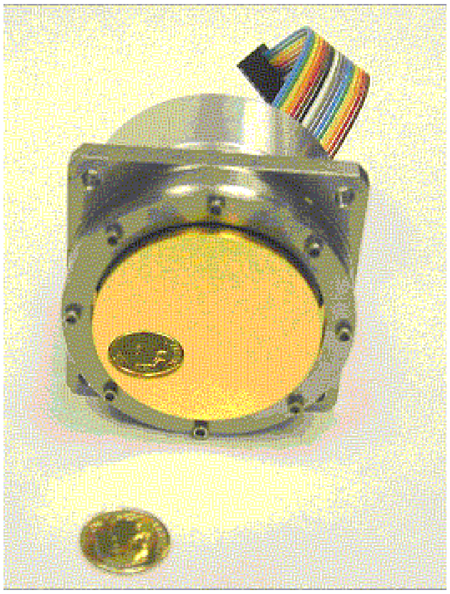


Figure 3: Photograph of a two axis FSM

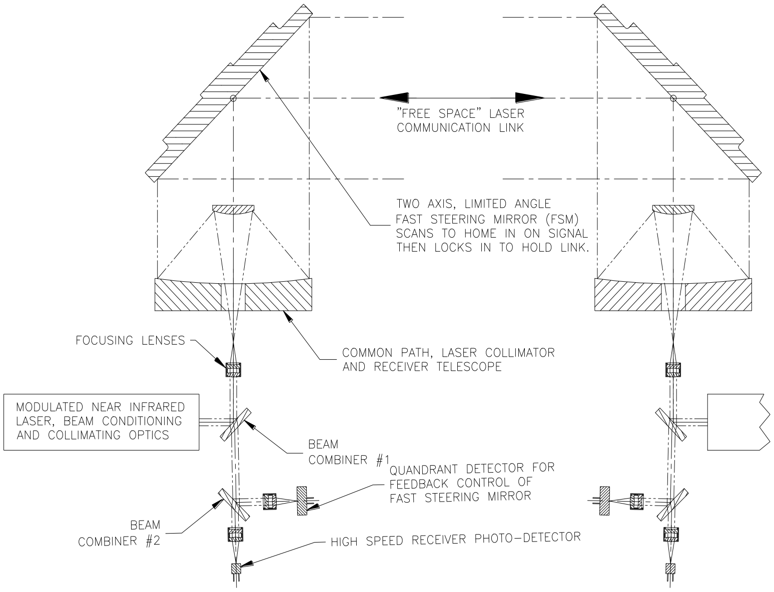


Figure 4: Schematic Diagram of a Free Laser Telecom Link

## FSM - Open and Closed Loop Control Systems

### Static Open Loop Performance

The FSM assembly consists of a mirror suspended on a two degrees of freedom flexure spring that enables the mirror to be tilted in the pitch and yaw directions. Two pairs of linear voice coil actuators are mounted on to the back of the mirror along the pitch and yaw axes, enabling electrical positioning control of the pitch and yaw tilt angles. Also mounted onto the base plate that supports the actuator housing is the Dual (Yaw & Pitch Axes) Analog Transconductance Power Amplifier printed circuit board, as well as two digital to analog converters that can provide digital interface from an external control system.

The voice coil actuators are current driven, thereby developing and applying a force vector to the flexure/mirror assembly resulting in an angular deflection. The angular deflection is in proportion to the analog command input voltage, as shown in figures 5 and 6, illustrating the angular mirror deflection as a function of control voltage for the y-axis and x-axis, respectively. These are actual plots of the measured data of a prototype FSM.

### Dynamic Open Loop Performance

The FSM mechanism contains elements of a classic spring-mass resonance system, i.e. flexure spring and mirror inertia, whose dynamic performance parallels that of classic second-order analysis used to evaluate the performance of second order-systems. To that end, the FSM was modeled using a popular Spice program with the results correlating to the bench testing data of the device.

The BODE plot of figure 7 reveals a 5 db peaking response at approximately 20 Hz, which compares with measured and calculated value of 23 Hz. The graph also indicates a bandwidth of approximately 35 Hz at –3db of attenuation. In figure 8, the position transient over-shoot response is approximately 40%, which corresponds with a 2nd order system damping factor of about Zeta = 0.35.

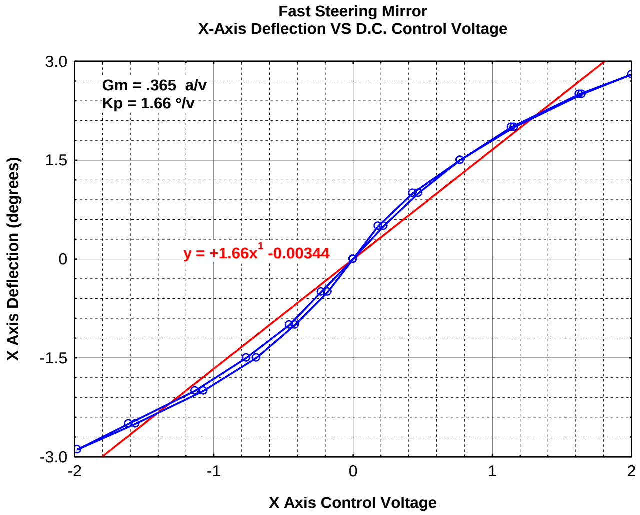


Fig. 5. Y-axis deflection VS control voltage

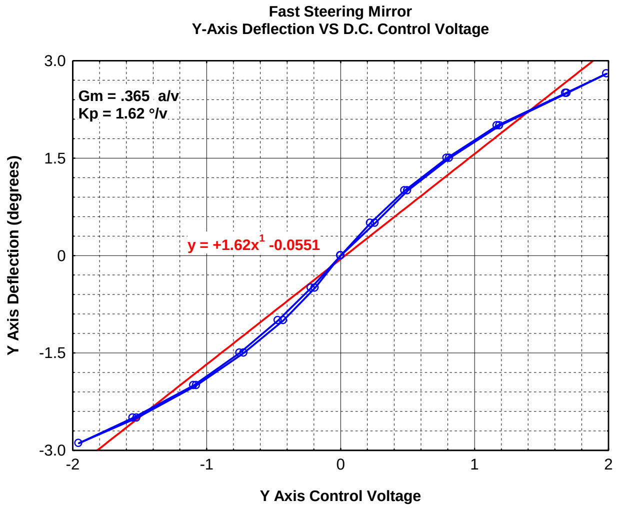
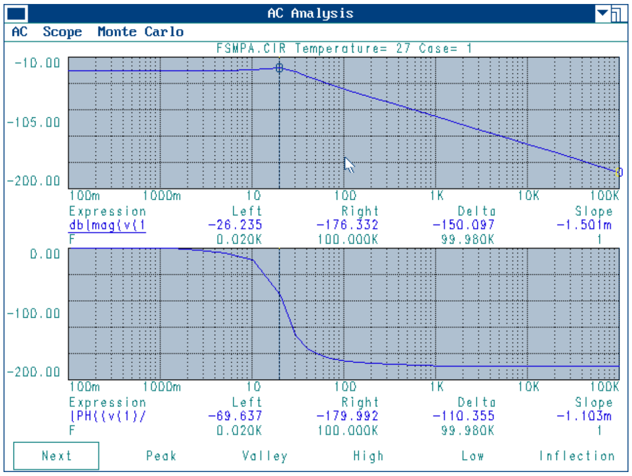


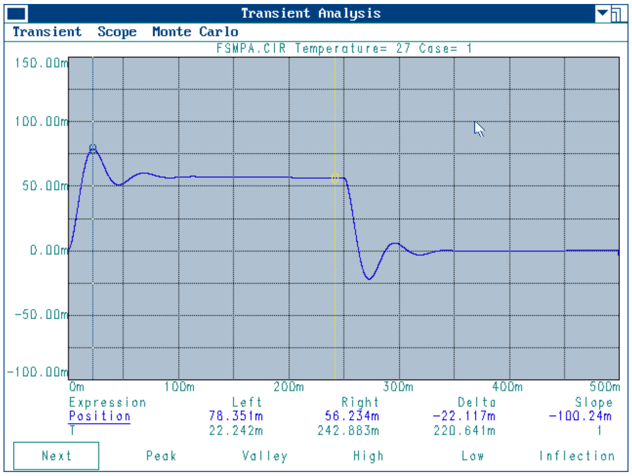
Fig. 6. X-axis deflection VS control voltage.

The graphs show that the best-fit equation describes a position gain of approximately 1.6 mechanical degrees per volt of control, and the deflection range of approximately +/- 3 degrees mechanical; also, the linearity range is within +/- 10% of full-scale deflection. If the device is operated in an open loop mode, it can serve as a course beam position control for instrumentation purposes or as a beam steering mechanism.



```
Expression       Left      Right      Delta     Slope
db(mag(v(1    -26.235   -176.332   -150.097   -1.501m
F              0.020K   100.000K    99.980K         1
```

```
Expression       Left      Right      Delta     Slope
(PH((v(1)/    -69.637   -179.992   -110.355   -1.103m
F              0.020K   100.000K    99.980K         1
```



```
Expression       Left      Right      Delta     Slope
Position      78.351m    56.234m   -22.117m  -100.24m
T             22.242m   242.883m   220.641m         1
```

Fig. 7. FSM – Position/Phase BODE plot.

Fig. 8. FSM - Position transient step response.

## Closed Loop Performance

With reference to Figure 9, the FSM can steer a laser beam to a remote optical pitch and yaw position sensor, whose digitized outputs are sent back to the local DSP servo controller for position control and stabilization. The DSP controller provides compensation for pointing errors detected by the remote optical angular position sensor.

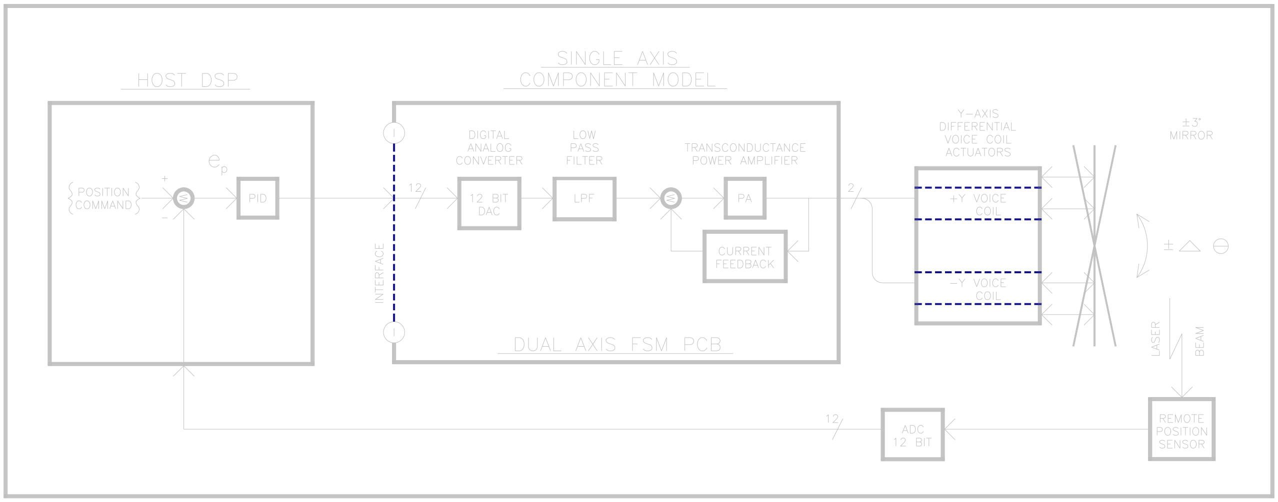


Fig. 9. FSM – Control System (single axis)

The FSM Controller System is a Type 2 control system which is defined as having zero steady-state error for a constant output displacement or velocity. The y-axis differentially connected voice coil actuators act in a push-pull manner tilting the mirror about a small virtual pivot point arc. The coils develop sufficient amount force to tilt the mirror/spring system to the commanded angular position as well as providing 800 radians per second squared of acceleration. The angular position of the steered laser beam is measured with the remote or local optical pitch & yaw sensors (lateral-effect or quadrant position detectors), and then differentially compared to the position command until the position servo error signal is driven to zero. The position error signal ($e_p$) is voltage amplified and processed through the network compensation and integrator circuits for damping control and integration. The PID output is fed through the transconductance amplifier and develops the necessary amount of torque to maintain commanded angular position.

## Transfer Function Model

The Analog Transfer Function Model, shown in Figure 10, consists of transfer function blocks with selected gain constants and motor parameters in a stable closed loop configuration. The position sensor gain constant, 100 volts/rad, determines the analog input position scale factor (Position Command in the DSP). The input error voltage is amplified with a gain of 100 using an instrumentation grade operational amplifier, or by digital means in the DSP, and is necessary to meet the 500 Hz target bandwidth goal. The amplifier output is processed through a passive lead/lag network with a lead break point of 500 rads/sec and a lag break point of 2000 rads/sec. The lead/lag network provides damping for about 1½ overshoots with a step function input command of 50 mrads. On a parallel path with the compensation network is an active integrator whose output is summed with the lead/lag output to reduce the servo error to zero, i.e. less than 100 urads.

The transconductance power amplifier outputs a current to the voice coil that develops a torque equal to the flexure spring torque required to position the mirror for a zero servo error at the input summing point, in the DSP. It can be shown that a current source effectively reduces the electrical time constant of the motor, resulting in a simple transfer function and faster response time. The voice coil torque constants and inertia have been selected to provide 800 rad/sec^2 maximum of acceleration with less than 1 amp of drive current.

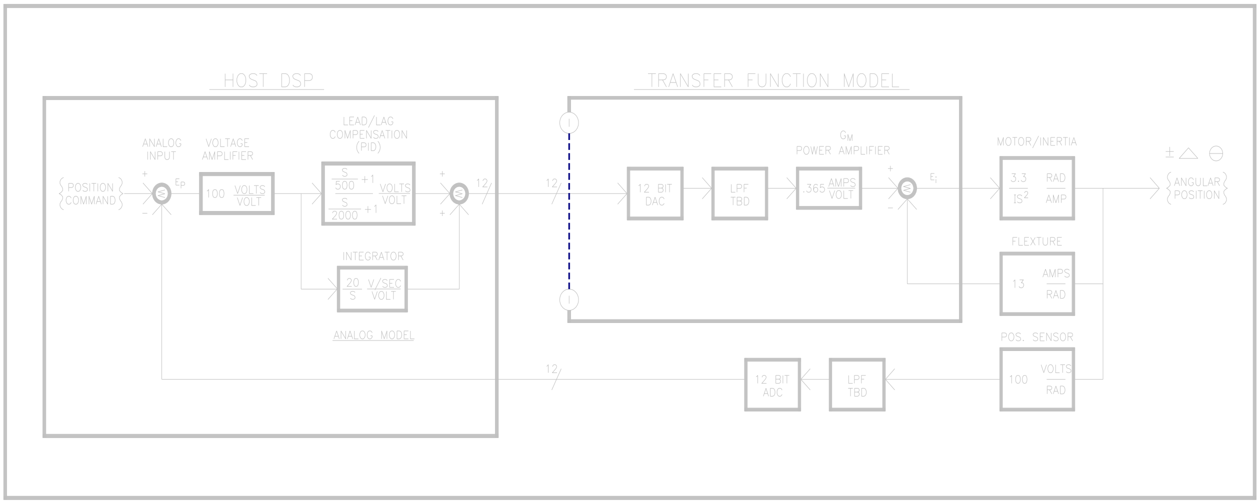
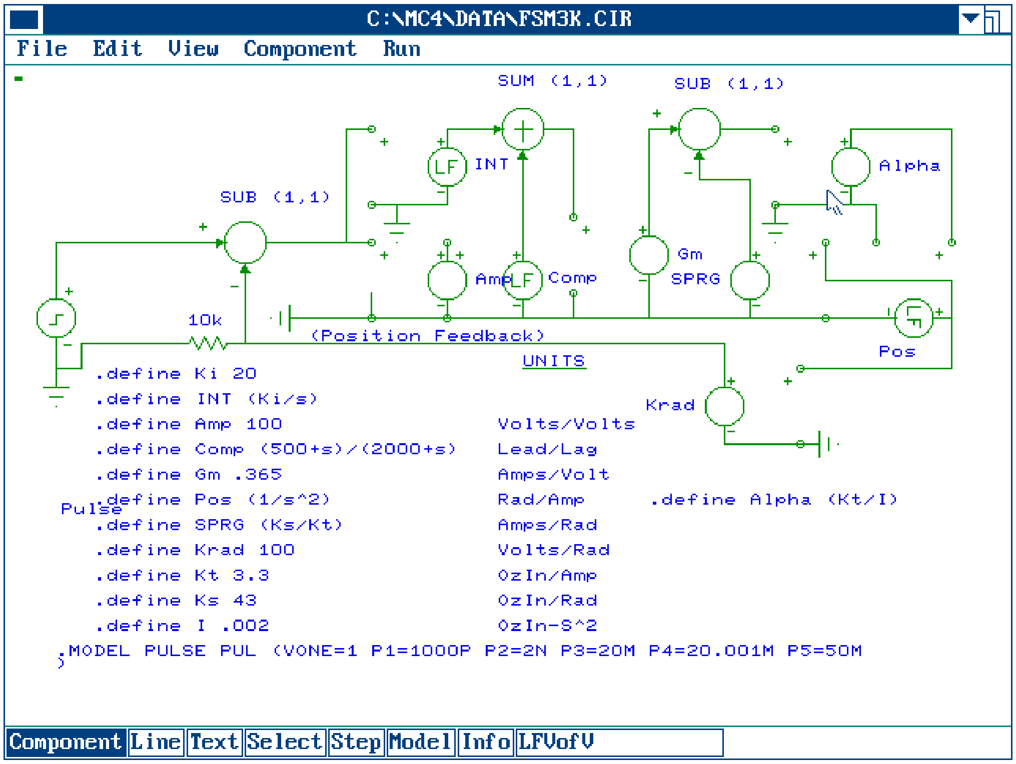


Fig. 10. FSM - Analog Transfer Function Model (single axis)

## Closed Loop Analysis Model

The Closed Loop Spice Model, Bode Plot, and Step Responses are shown in Figures 7, 8, and 9, respectively. Included with the Spice model are the definitions of the selected constants and transfer functions of the elements and their associated units.



```
                                        UNITS
.define Ki 20
.define INT (Ki/s)
.define Amp 100                       Volts/Volts
.define Comp (500+s)/(2000+s)         Lead/Lag
.define Gm .365                       Amps/Volt
.define Pos (1/s^2)                   Rad/Amp       .define Alpha (Kt/I)
.define SPRG (Ks/Kt)                  Amps/Rad
.define Krad 100                      Volts/Rad
.define Kt 3.3                        OzIn/Amp
.define Ks 43                         OzIn/Rad
.define I .002                        OzIn-S^2
;MODEL PULSE PUL (VONE=1 P1=1000P P2=2N P3=20M P4=20.001M P5=50M
```

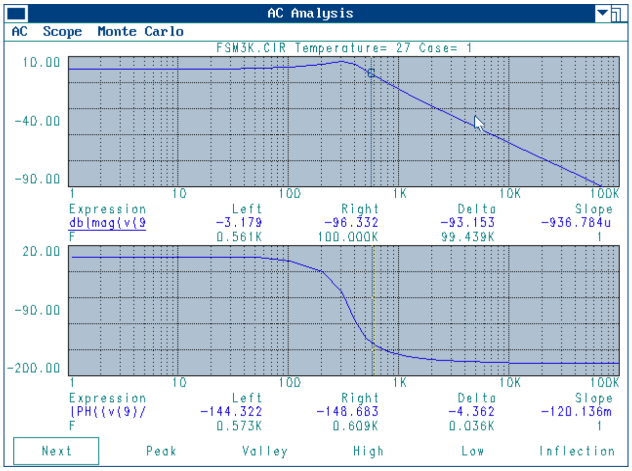
Fig. 11. Closed Loop Spice Model (single axis)

## Closed Loop Position/Phase BODE plot

The Closed Loop BODE plot of figure 12 reveals a bandwidth of 560 Hz, which is over an order of magnitude improvement when compared to stand alone Open Loop FSM's bandwidth of 35 Hz. The phase shift at the –3db point is approximately –145 degrees resulting in a phase margin of 35 degrees. Also shown is a small amount of peaking at about 300 Hz of approximately 8 db. These performance parameters can be optimized by hand tuning the system at installation.

## Closed Loop Position Transient Step Response

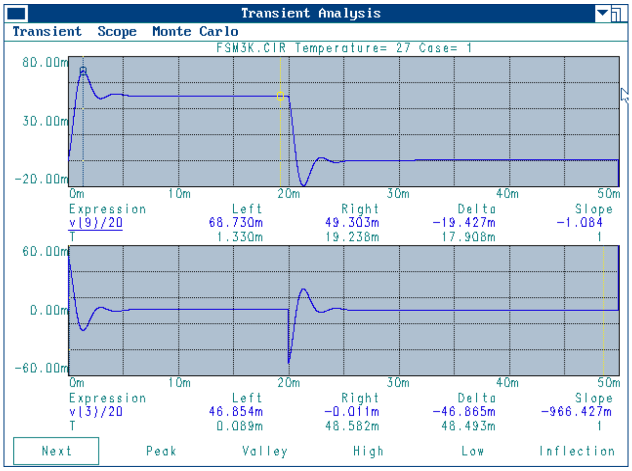
The step response plot, Figure 13, shows the output position response to a 50 mrad step input (approximately 3 degrees), to be 1 ms at 50 mrads. Also shown is the position settling time of about 20 ms with an error of about 700 urads less than 50 mrads. The second plot is the instantaneous servo error, as the difference between the step command and the feedback response. Note that the settling at 50 ms is shown to be 11 urads. As stated before, these parameters can be changed and optimized to the application at installation.



```
Expression          Left       Right       Delta        Slope
db(mag(v(9        -3.179     -96.332     -93.153    -936.784u
F                 0.561K    100.000K     99.439K            1
```

```
Expression          Left       Right       Delta        Slope
(PH((v(9)/      -144.322    -148.683      -4.362    -120.136m
F                 0.573K      0.609K      0.036K            1
```

Fig. 12. FSM – Closed Loop Position/Phase BODE plot.



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Expression          Left       Right       Delta        Slope
v(9)/20          68.730m     49.303m    -19.427m       -1.084
T                 1.330m     19.238m     17.908m            1
```

```
Expression          Left       Right       Delta        Slope
v(3)/20          46.854m     -0.011m    -46.865m    -966.427m
T                 0.089m     48.582m     48.493m            1
```

Fig. 13. FSM – Closed Loop Position Step Response.

## SUMMARY:

Flexure suspended Fast Steering Mirrors (FSM's) represent a growing class of design solutions for a variety of beam steering and beam stabilization problems. Innovative designs of flexures can result in low power consumption and expanded range of motion while retaining high rigidity in the non-compliant degrees of freedom. The design of the flexure system is critical to virtual pivot placement, and achieving smooth, repeatable, and uncoupled motion.

In general the type and range of motion, dynamic response, mirror aperture, and tolerance on mirror flatness define the solution space for development of the mirror flexures, actuator type and characteristics, and control system requirements.

The use of metal mirrors provides the opto-mechanical engineer with the opportunity to experiment with integrally machined flexures and high stiffness fastening approaches that do not require the use of adhesives. Materials having exceptional specific stiffness, such as beryllium, can further extend the horizons for metal mirror designs in particularly demanding applications where performance outweighs added input material and processing costs. Light-weighting techniques are also readily applied to the design of metal mirrors to optimize the structural efficiency and maximize the frequency response of the selected actuators and accompanying control system.

Voice coil and piezoelectric actuators are the most common types applied to FSMs. The type, performance characteristics, and number of actuators used in an FSM design is highly application specific. A variety of off-the-shelf components and custom actuator development services are available within the industry.

A single axis FSM used to correct polygon cross scan error is presented herein as the design solution for a successful flat field scanning system used in electronic prepress photography. Similar approaches can be applied to a wide variety of polygon inspection and writing engines.

A dual axis FSM used to establish and then maintain a free space laser telecommunication link is also presented. Such a device has broad application to general beam stabilization problems caused by environmental stresses and drift. Unlike resonant scanners and constant velocity rotating scanners, the FSM also provides a non-cyclic scanning alternative over a limited range of frequencies and angles. An overview of feedback controls system tradeoffs is also presented for this application. Control systems for FSM's can be modeled with computer aided design tools with very predictable results.

## REFERENCES:

1. Sweeney, M. N. "Polygon Scanners Revisited" Proceeding SPIE volume 3131, July 1997

2. Hecht, Jeff "New Applications put an old idea back in the air" Laser Focus World, Nov. 2001

3. V. Mitchell, et al "Fast-steering mirrors improve active beam stabilization" Optoelectronics World, October, 2001

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