INVERSE SYSTEM FILTER FOR MEMS MIRRORS
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MEMS Mirror Key Facts

- Mirrorcle Technologies' MEMS mirrors are made entirely of monolithic single-crystal silicon, resulting in excellent repeatability and reliability. Mirror surfaces are coated with a thin film of metal with high broadband reflectance (standard coating materials are Au or Al).
- Smaller and medium mirror sizes are manufactured as integrated parts of the silicon MEMS chip, while larger mirrors are bonded onto MEMS actuators, allowing for custom mirror sizes.
- Positional precision of mechanical tilt in open loop driving of the mirror actuators is at least 14 bits (16384 positions) on each axis. For most devices, with mechanical tilt range of \(-5^\circ\) to \(+5^\circ\) on each axis, this tilt resolution is within 0.6 millidegrees or within 10 micro-radians.
- The mirrors deflect laser beams or images to optical scanning angles of up to 32° on each axis.
**SPEED:** Devices with larger-diameter mirrors are correspondingly slower due to increased inertia (for a given actuator). Inertia of a round mirror is proportional to the fourth power of the radius. Therefore, for a given actuator, speed reduces quadratically (square power) with an increase in mirror size. For example, to compare two integrated mirrors, a 0.8 mm with a 1.7 mm diameter, both having the same silicon die size and both having very similar mechanical tip/tilt angles. The 0.8 mm device’s first resonant frequency is approx. 4 kHz, while the 1.7 mm device’s is approx. 1.2 kHz.

**COST:** One design parameter with a strong influence on key performance specifications is mirror size. To allow for fast speeds, larger mirrors require larger actuators which generally provide higher forces and torques; with increasing actuator die size more complex designs are often required. Additionally, larger die may require larger packages.

**ROBUSTNESS:** Devices with smaller-diameter mirrors generally exhibit higher shock and vibration tolerance due to lower mass and angular inertia.
Integrated mirrors are monolithically fabricated as an integrated part of the gimbal-less actuator device structure.

As the center of mirror inertia is approximately in the plane of the actuator’s rotating axis, they can be approximated with simple $2^{nd}$ order models.
Integrated MEMS Mirrors Overview

- Its response can be approximated by a damped harmonic oscillator (specifically 2\textsuperscript{nd} order spring-mass system)

\[
\frac{d^2\theta}{dt^2} + 2\cdot\zeta\cdot\omega_n\cdot\frac{d\theta}{dt} + \omega_n^2\cdot\theta = 0
\]
The High-Q Problem – Overshoot and Ringing
We must apply only forces in the “green” region which will not excite resonant or over-amplitude response.

The simple solution is to LPF sharply somewhere well before $\omega_n/2$
- Butterworth, Bessel filters

Speed is limited and can never compete with closed loop response

Type of filter still critical, i.e. group delay response
Closed-Loop PD Control

Step response settling times with optical feedback and PID control are 2-3 times better than in simple LPF open loop control.

But – a position sensor is required and more complex electronics.
Inverse System Filter Solution

![Bode Diagram Image]

Inverse System Filter Response
Final Response
Raw System Response

Inverse System Filter Response
Final Response
Raw System Response

Works great for small signals and is more limited for large signals.

\[ H^{-1}(s) \cdot \frac{p_1 \cdot p_2}{(s - p_1)(s - p_2)} \]
Example of Input to Output

MEMS Model

Mechanical spring-mass system response

\[ H(s) = K \cdot \frac{\omega_n^2}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2} \]

Mirror angle

Control Voltage

\( V_{\text{difference}}(t) \)

Driving the MEMS with the Inverse System Filter

Inverse System Filter with 2 added poles

\[ H^{-1}(s) \cdot \omega_{F1}^2 \]

\( s + \omega_{F1} \)

Mechanical spring-mass system response

\[ H(s) = K \cdot \frac{\omega_n^2}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2} \]

Mirror angle

Control Voltage

\( V_{\text{difference}}(t) \)

2 or 3 additional poles are added to reduce the overall bandwidth and overshoot voltages. For example, allowing bandwidth 2\( \ast \) the resonance could already be very useful but not introduce very large overshoot voltages. Two or 3 poles at that frequency can be added to complete the inverse system filter into a realizeable software/firmware or even hardware filter:

\[ \omega_{F1} = 2 \ast \omega_n \]
Open-Loop ‘Inverse System Filter’ Control
Closing Comments and Disclaimer
Closing Comments

- The models are approximate and assume linear response which is not true in reality at all angles etc.

- Damping is also approximated as it is ultimately a function of angle.

- Note that for different Vbias setting, the gain factor $K_{\text{new\_bias}}$ can be estimated from a known $K_{\text{known\_bias}}$ as follows: $K_{\text{new\_bias}} = K_{\text{known\_bias}} * \frac{V_{\text{bias\_new}}}{V_{\text{bias\_known}}}$
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Thank You for Choosing