INPUT SHAPING FOR OPEN LOOP CONTROL OF MEMS MIRRORS
MEMS Mirror Device – Frequency Response

- Mirrorcle’s integrated MEMS mirrors can be modeled as 2nd order spring-mass systems with a high-Q resonance.
  - Mirrorcle’s bonded MEMS mirrors can be similarly modeled as 4th order mass-spring systems
  - For more information, see App Note: Approximate Linear Models for MEMS Mirrors
- Goal of input shaping schemes is to avoid excitation of resonant response with overshoot and ringing (oscillation, see images).
- A low-pass filter is the standard tool for suppressing excitation of device resonant response to high-frequency drive signals (e.g. abrupt voltage steps or impulses)
- Mirrorcle’s USB MEMS Controllers and MEMS Drivers have an onboard 5th order Bessel Low-Pass Filter

Small-signal frequency response (magnitude) and step response for an integrated MEMS mirror (2nd order)

Small-signal frequency response (magnitude) and step response for a bonded MEMS mirror (4th order)
MEMS Mirror Device – Quasi-static Response

- Ideally, MEMS Mirror responds with angle proportional to input voltage when input voltages are at relatively low frequencies.
- This region of lower frequencies where excitation results in (normalized) unity response, is the Quasi-static Response region.
- To operate in this region, we must shape input waveforms to ensure they do not include frequency content above the region (e.g. near resonance), either with time domain methods such as special interpolations, or with frequency domain methods such as filtering.
- However, all such approaches have a limitation in cases where devices do not respond proportionally (nonlinear response).
**Quasi-static Response — Linear vs. Nonlinear**

- **Electrostatic forces are** proportional to $V_{\text{difference}}$ squared — **inherently nonlinear**.

- The Biased Differential Quad-channel (BDQ) driving scheme of Mirrorcle MEMS Mirrors **linearizes the response of the electrostatic combdrive** architecture from origin to large negative and positive angles.

- Nevertheless, **most designs are used beyond the linearized region** of response, and at larger angles show **sublinear response to drive voltage** ($V_{\text{difference}}$).

- The nonlinear aspect of response, even if small, can cause excitation of resonance even with voltage waveforms strictly in **quasi-static response region**.
MEMS Mirror Device – Nonlinearity in Static Response

- Drive voltage from a MEMS Driver is transformed into rotational torque of the combdrive which is nominally linear based on its special design and based on driving with differential signals about a bias point*. In reality the transformation is not fully linear, especially going sub-linear in higher angles where the torque begins to diminish near combdrive’s rotational limit.

- Thus the combdrive torque (and angle response) has higher order terms when viewed as a Power series. Due to the symmetry and bias-differential driving only the odd terms of the power series are significant:
  - As an example, \( T \propto V - 10^{-5} \cdot V^3 + 10^{-10} \cdot V^5 - 10^{-15} \cdot V^7 \), where \( T \) is rotational torque of the combdrive, and \( V \) is \( V_{\text{difference}} \) driver voltage (difference about a bias \( V_{\text{bias}} \)) which is proportional to user’s command voltage.
  - Matching the image example, if drive voltage \( V \sim \sin(\omega t) \) at 128Hz, then the torque includes frequencies \( \sin(3\omega t) \), \( \sin(5\omega t) \), \( \sin(7\omega t) \), where \( 7\omega t \) directly excites 900Hz resonance!

- The higher terms can unfortunately multiply frequencies of drive signals and excite torques at frequencies well above the drive.

In general, excitation of the MEMS resonant response is well-controlled by implementing a low-pass filter in series with the drive signal.

However, waveforms consisting of frequencies that are \( \frac{F_{res}}{2n+1} \) can excite a harmonic response from the MEMS mirror.

This excitation is reduced when driving at frequencies slightly above or below the subharmonics by a few Hz. (avoiding \( \frac{F_{res}}{2n+1} \) in drive)
Correcting for Device Response (open loop)

- **Low-pass filter**

- **Inverse system filter**
  - An inverse of the MEMS mirror response can be created to suppress the resonant peak of the device and extend the device’s bandwidth.
  - More information: [Closed-Loop Control of Gimbal-less MEMS Mirrors for Increased Bandwidth in LiDAR Applications](#)

- **Look-up table (LUT)**
  - A voltage vs. angle look up table to linearize the device’s response over the entire field of view.

- **Polynomial**
  - A voltage vs. angle polynomial fit to linearize the device’s response over the entire field of view.
Correcting for Device Response (closed loop)

- **Iterative Learning Control**
  - Training the waveform with iterations with a position sensor to adjust within a very small error (10s of millidegrees) from the desired device
  - More information: *Iterative Learning Control Algorithm for Greatly Increased Bandwidth and Linearity of MEMS Mirrors in LiDAR and Related Imaging Applications*

- **Closed Loop Control (PID)**
  - Add a real-time position feedback sensor and close the loop.
  - More information: *Closed-Loop Control of Gimbal-less MEMS Mirrors for Increased Bandwidth in LiDAR Applications*
For recommended approaches and ability to experiment and develop solutions with different input shaping approaches, filtering approaches etc, it is strongly advised to use a Mirrorcle USB MEMS Controller and Software Suite.
Recommendation 1 – Use quasi-static response region

- Waveforms should be generated with frequencies that fall within the quasi-static response region of the device.
- This is from dc (0Hz) to approximately $f_{\text{res}} / 2.5$
- All components of the content waveform (when looking at its power spectrum or FFT) should be in that region, not only the major frequency component such as the one based on e.g. waveform period.
- This can be done in time domain by careful interpolation to avoid high acceleration, deceleration between keypoints.
- This can also be done in frequency domain by filtering final waveform.
- Both approaches are used in Mirrorcle software, with trapezoidal interpolation first, then filtering.
Recommendation 2 – Avoid sub-harmonics of resonance

- For the main components of the waveform such as the selecting the period itself of a line raster for example, avoid subharmonics of the device resonant frequency.

- Odd subharmonics such as $f_{res}/3$ and $f_{res}/5$ have the strongest impact. And anything within $\pm 10\%$ of that number may have impact.

- For example, on a 900Hz $f_{res}$ device, do not design to run sawtooth waveforms or even sine waveforms at 300Hz, or 180Hz, or 128Hz, or 100Hz... See if you can work with in between values for the main repetition rate of your waveform.

- Note that for small-angle waveforms this may not be significant since response may be mostly linear – but for any waveforms that demand large angle scans it is.
Recommendation 3 – Linearize device response

- If possible, try to provide excitation waveforms that are linear with torque and not with voltage. For example to get a sinusoidal scan of the mirror, you want to apply sinusoidal torque and not voltage.

- Therefore device response should be measured by a calibration method (sensor, wall markers etc), and a look up table of V difference to Angle should be created.

- Either use of an inverse look up table (iLUT) can linearize the device response, or use of a polynomial fit for the V difference to Angle response.

- Therefore after creating desired scan waveform, pass through a transform function which reverses the V to Angle non-linearity.
Recommendation 4 – Use hardware filter

- The hardware low pass filters (LPFs) on-board the Mirrorcle MEMS Drivers can remove any final unwanted higher frequencies which escaped the software input shaping or possibly result from DAC/amplifier circuitry.

- Hardware filter cut-off is typically recommended at $f_{\text{res}}/2.5$
Thank You for Choosing

Additional Resources:

- Mirrorcle MEMS Mirrors — Technical Overview
- Mirrorcle Documentation Portal
- Mirrorcle Web Page — Support
- Mirrorcle Web Page — Application Notes
- Mirrorcle Web Page — Publications

If you have any further questions or suggestions please email us:
support@mirrorcletech.com