"Valves Tapping in Rhythm"

Electro-Mechanical Valve (EMV) Actuator Control for Camless Engines

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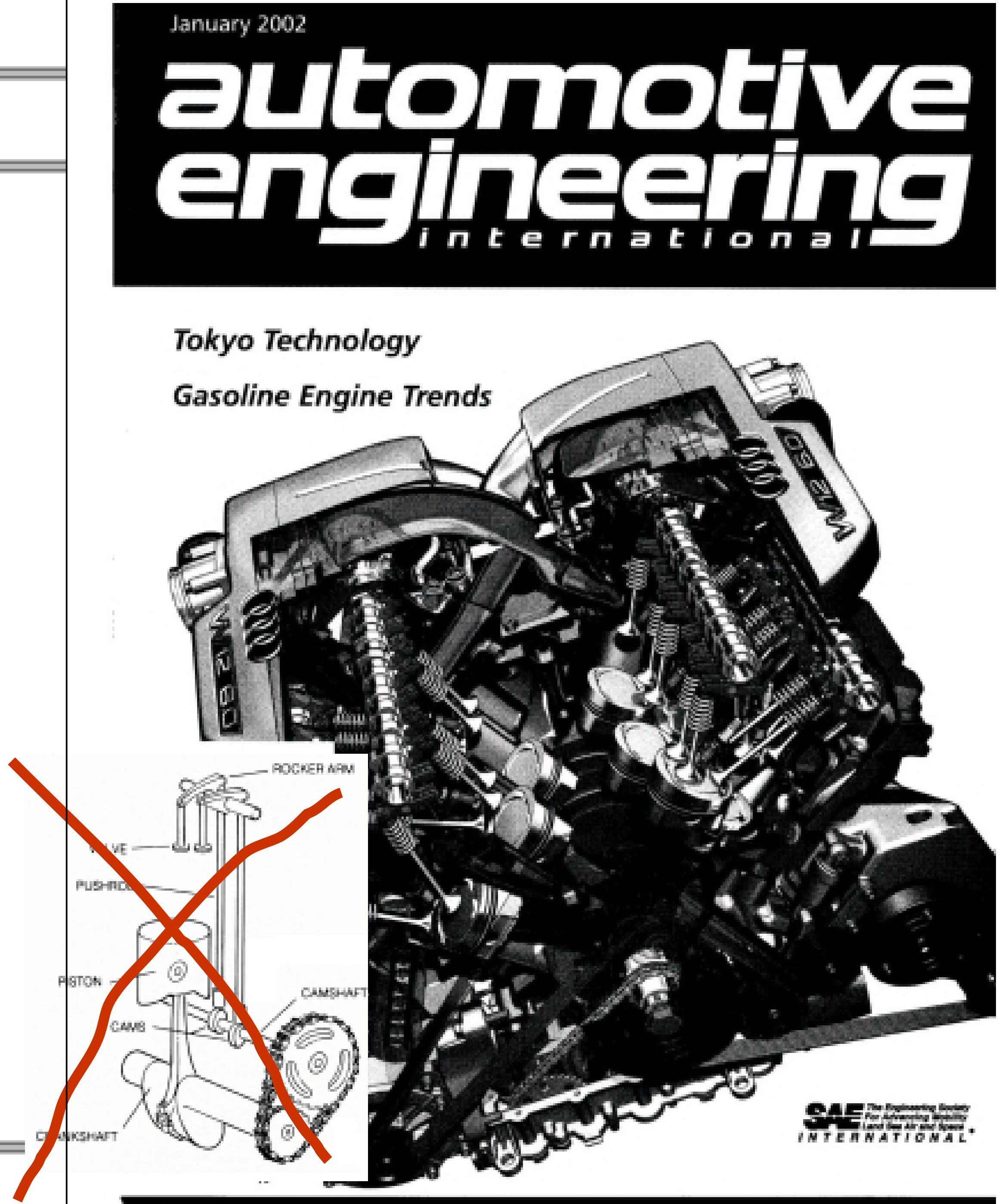
The Mohammed Dahleh Symposium

Powertrain
Control Lab

Thanks to NSF (ECS-0049025), Ford Motor, and Volvo Cars

Gasoline Engine Trends

"Apart from our focus on hydrogen as the fuel of the future, Valvetronic is a decisive technology in reaching our CO2 objectives in the future."
B. Goschel, BMW



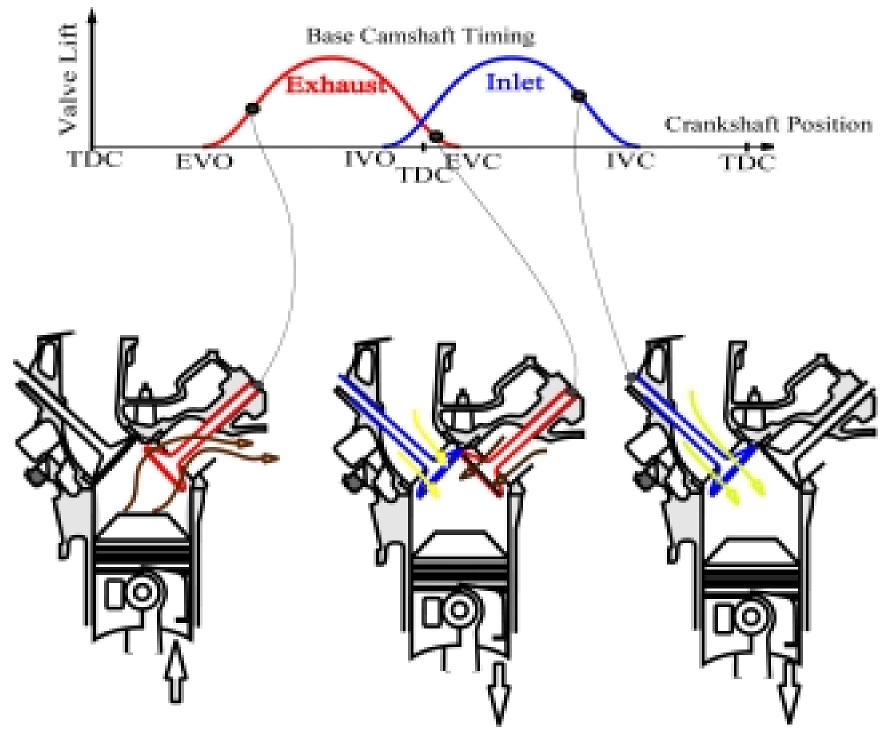
From Cam-Variable to Cam-Less

- **Better fuel efficiency**
  - **Less pumping loss (Levin et al)**
  - **Cylinder deactivation (Hatano et al)**
  - **Improvement is up to 10-15% (Kreuter et al)**

- **Increased torque output**
  - **Ramming effect during high engine speed**
  - **Improvement is up to 20% (Hatano et al)**

- **Elimination of external Exhaust Gas Recirculation (EGR)**

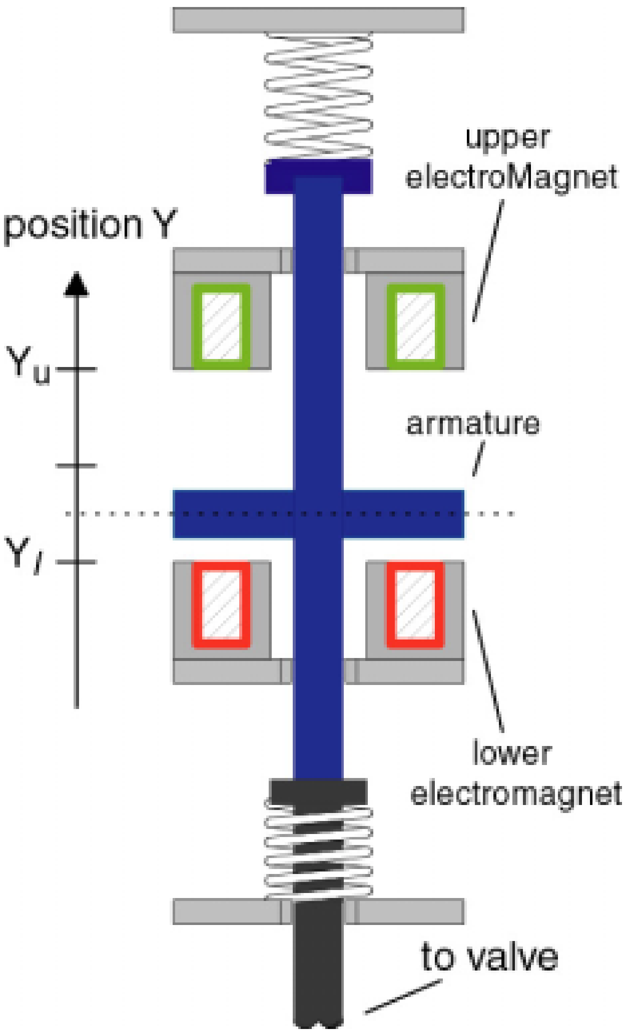
- **Reduced emissions**
  - **Reduction of NOx is up to 40% (Moriya et al)**
  - **Reduction of HC is up to 15% (Lancefield et al)**
  - **Reduction of CO is up to 5% (Gould et al)**

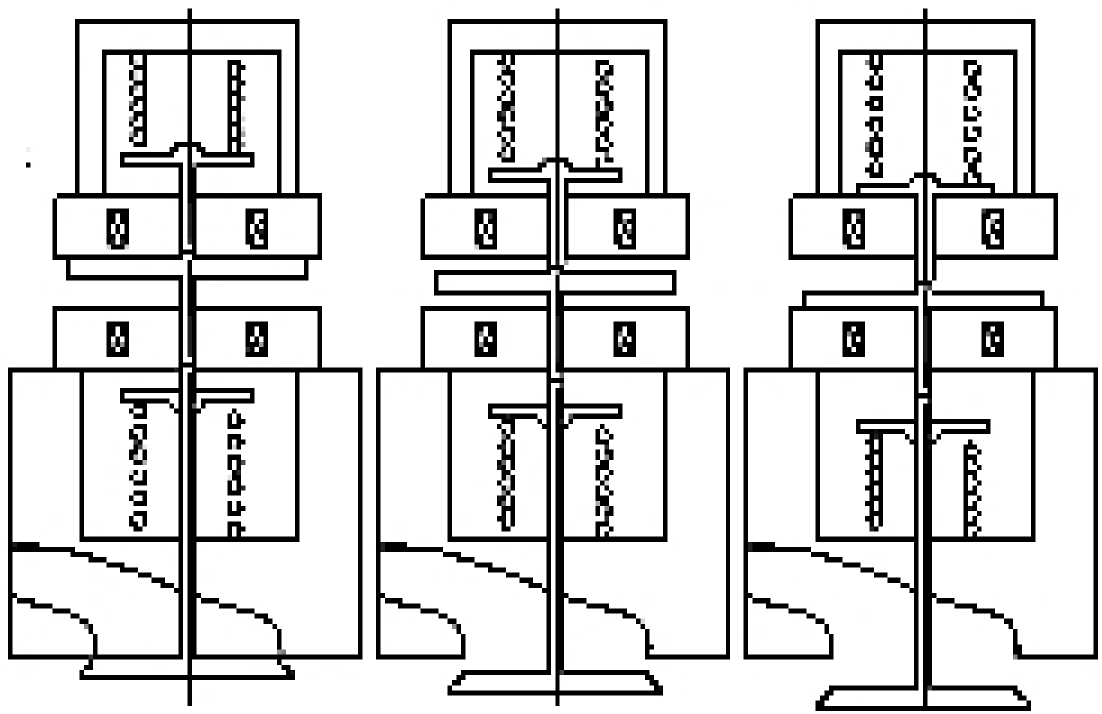


Contents:

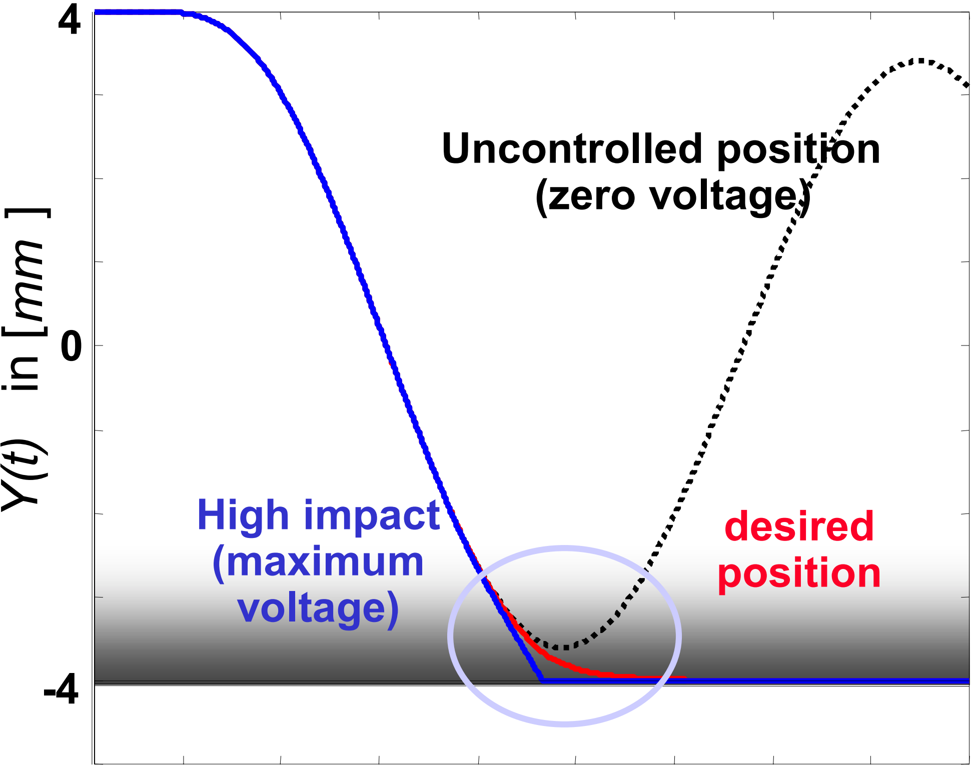
- How does the EMV actuator work
- The Control Problem
- Feedback controller
- Self-tuning

Electro-Mechanical Valvetrain (EMV)





Problem: Fast Transition and Soft Landing



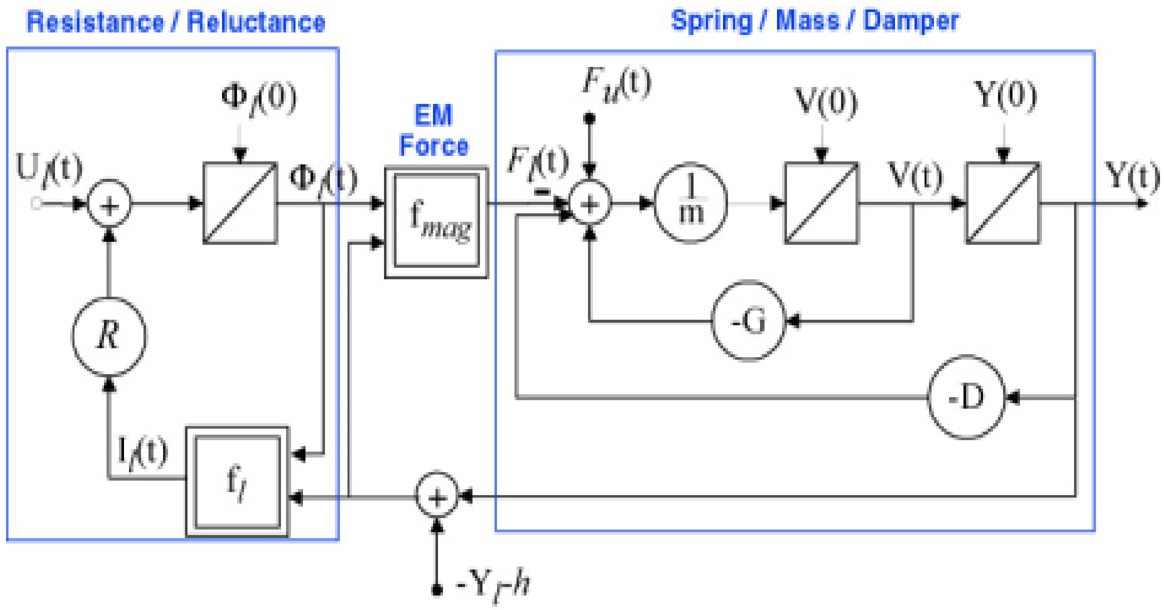
PROBLEM

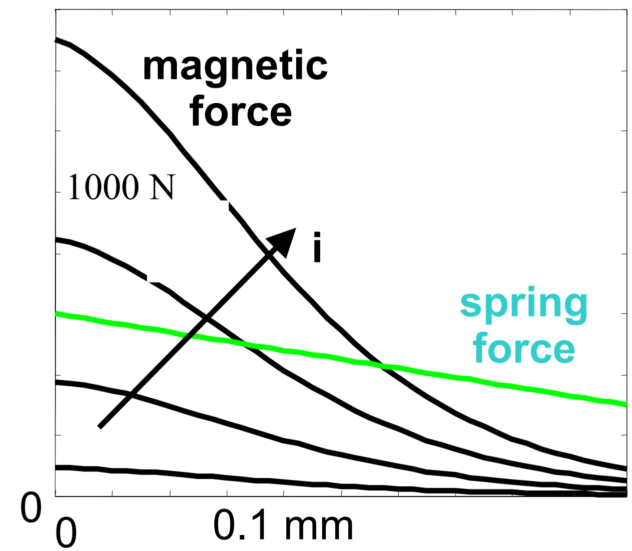
- **Voltage too high: velocities > 1m/sec noise and component wear**
- **Voltage too low: accurate closing not ensured**

GOAL

- **Impact velocities of less than 0.05 m/s**
- **Consistent transition times of approximately 4 ms**
- **Rejection of disturbance due to pressure differences**

Difficulties

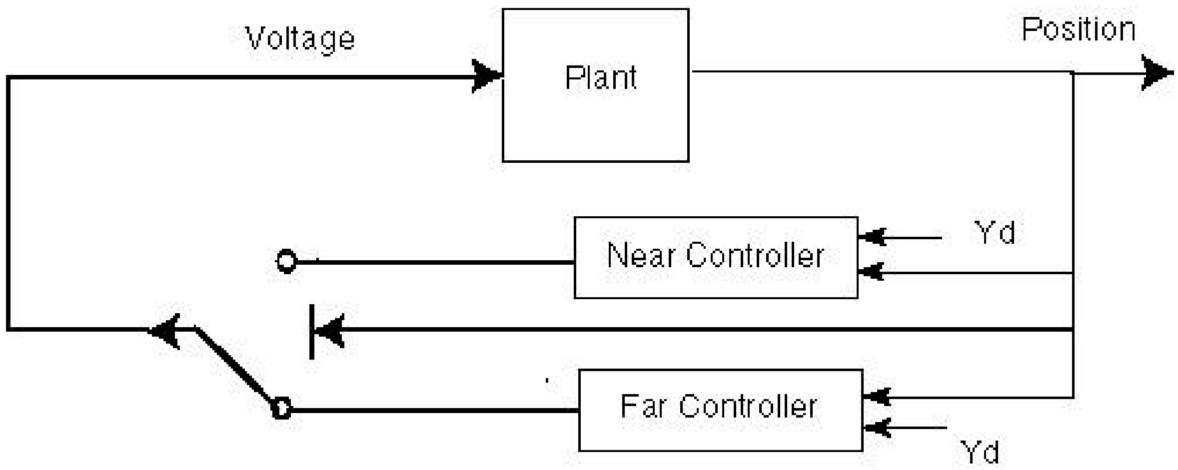




<u>Feedback control difficulties</u>

- Unstable system close to the contact point
- Actuator authority range and saturation
- Nonlinear magnetic force
- Uncertain system parameters close to the contact point

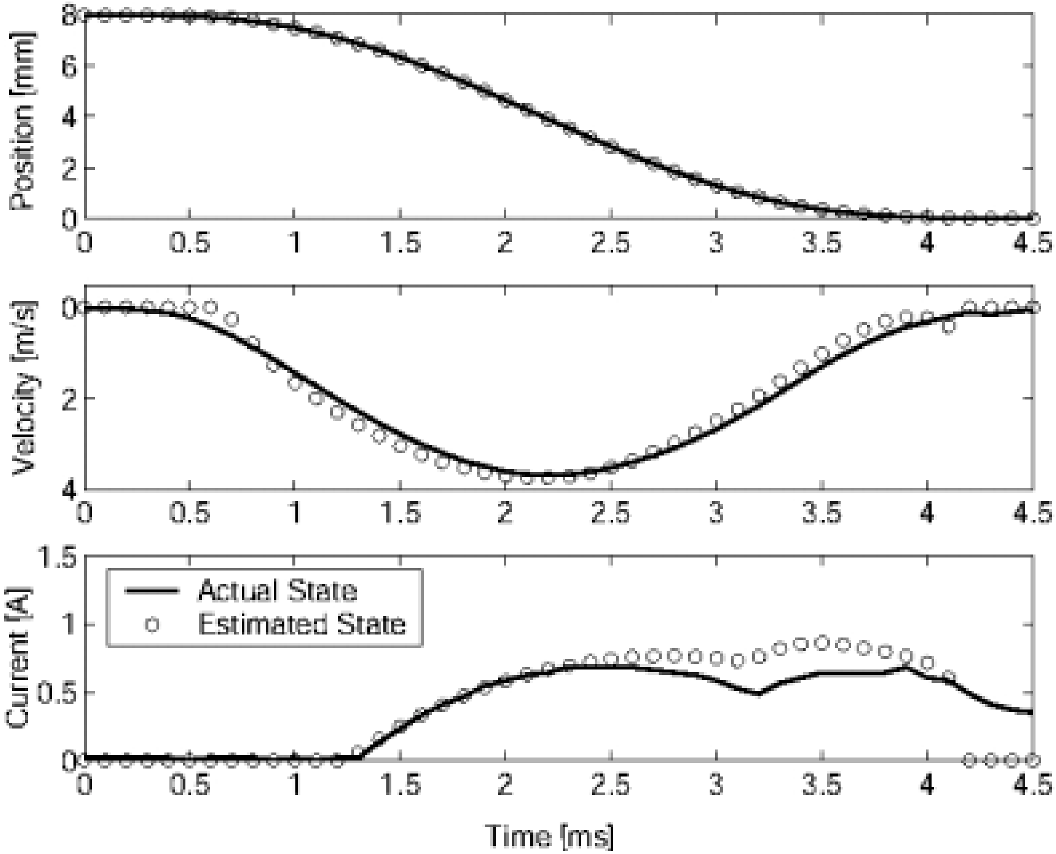
Linear Feedback Control design



- Linearization at two equilibrium points in the transition trajectory
- Switch between two linear feedback controllers
  - Flux initialization (penalty on current)
  - Regulation (penalty on position)
- Observer for velocity and current

State Observer (+controller)

Discrete Nonlinear Reduced Order observer



Current is nearly unobservable

- Magnetic force has weak influence on valve motion while the armature is away from the contact position
- Near the contact position, the magnetic force is more strongly influenced by changes in position then changes in current
- Sampling: 20Khz

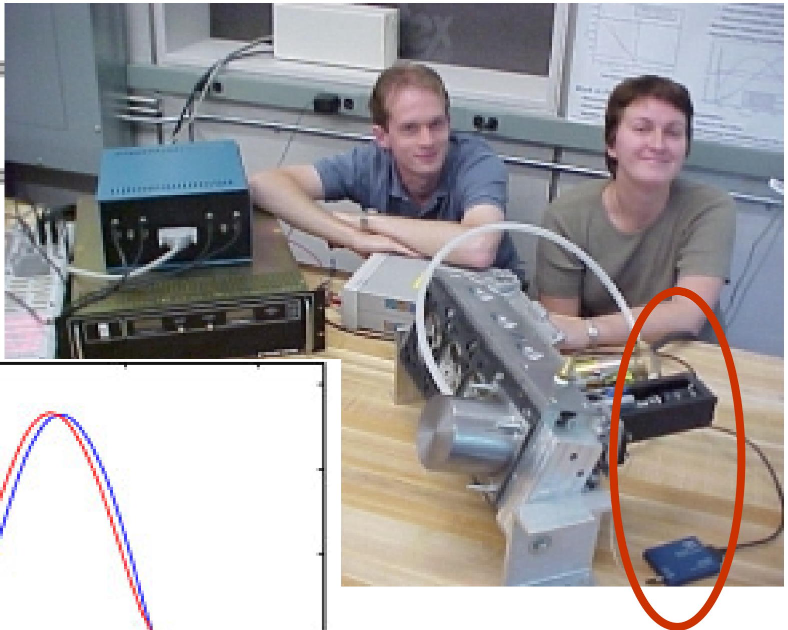
  - **Impact Velocity**

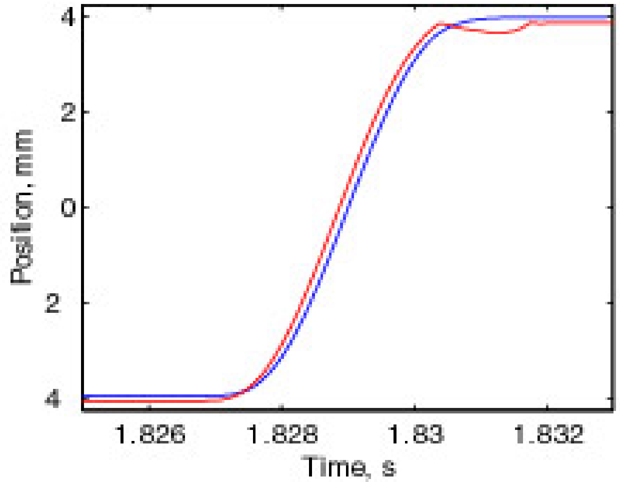
  Mean=0.15 m/s (σ=0.1 m/s)

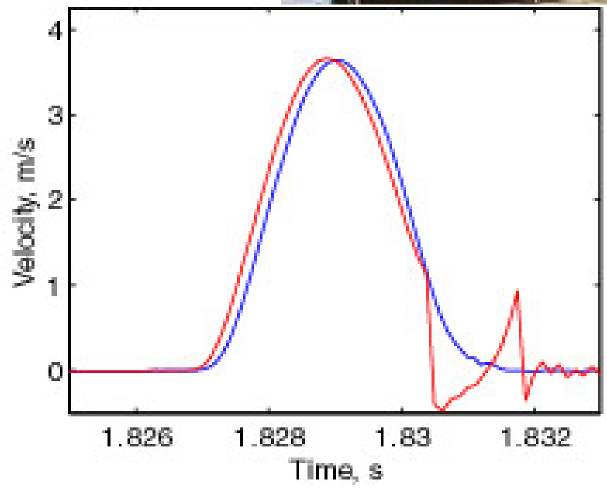
  - **Transition Time**

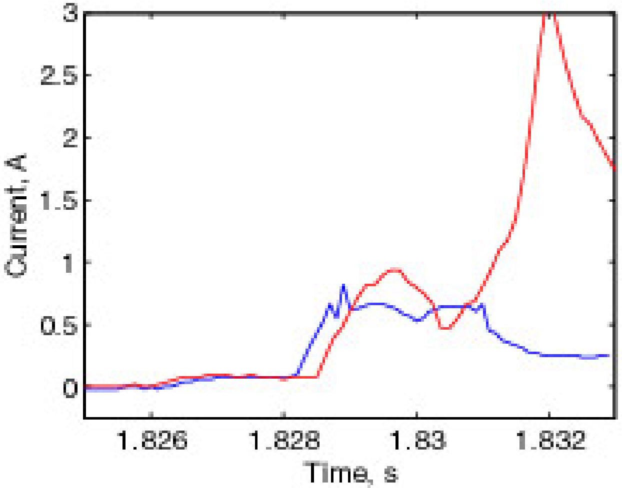
  Mean=3.25 ms (σ=0.04 ms)

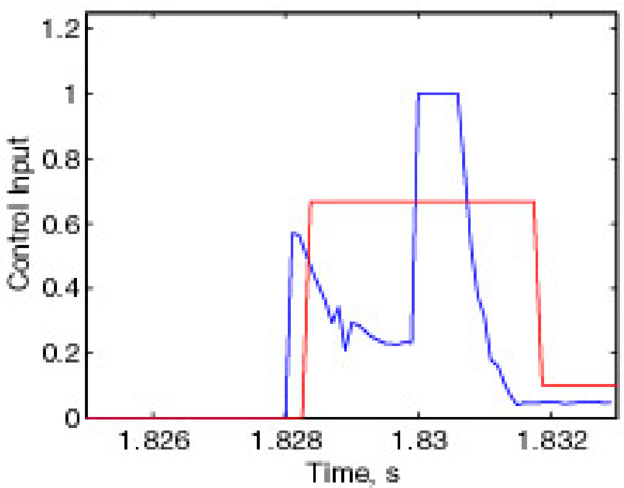
Implementation











<u>Thanks to:</u>

Yan Wang (UCSB)
Garrick McNey (UCSB)
Kathy Peterson (UMICH)
Richard Kors (UMICH)

and

Brad and Lena Paden!

Looking at the Dynamics

$$\frac{di}{dt} = \frac{V_c - ri + \chi_1(z,i)v}{\chi_2(z)}$$

$$\frac{dz}{dt} = 1000v$$

$$\frac{dv}{dt} = \frac{1}{m}\left(-F_{mag}(z,i) + k_s(4-z) - bv\right)$$

$$\chi_1 = \frac{2k_a i}{(k_b + z)^2},$$

$$\chi_2 = \frac{2k_a}{1000(k_b + z)}$$

$$F_{mag} = \frac{k_a i^2}{(k_b + z)^2}$$

$$k_b << 1 \quad \& \quad z \to 0$$

$$\Rightarrow \text{let } \varepsilon = k_b + z$$

$$\Rightarrow \varepsilon\frac{di}{dt} = 1000\left(\frac{(V_c - ri)\varepsilon^2}{2k_a} + iv\right)$$

Effects:

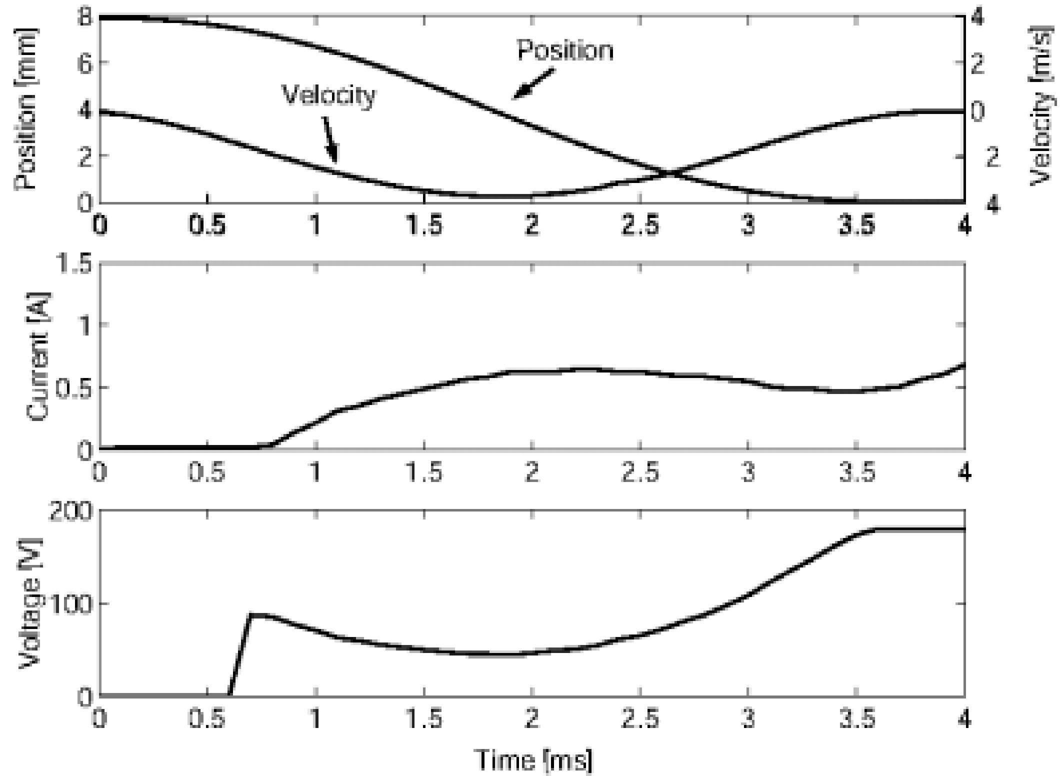
- Loss of Control Authority
- Current becomes singularly perturbed

Nonlinear Controller

$$V_c = \frac{K_1}{\gamma + z} v + \frac{K_2}{\beta + \frac{z}{\kappa}}$$

<u>Addresses:</u>

- ✓ Loss of Control Authority
  - The feedback is inversely proportional to the position
- ✓ Impact
  - The voltage is controlled to account potential bouncing



- **Impact Velocity**

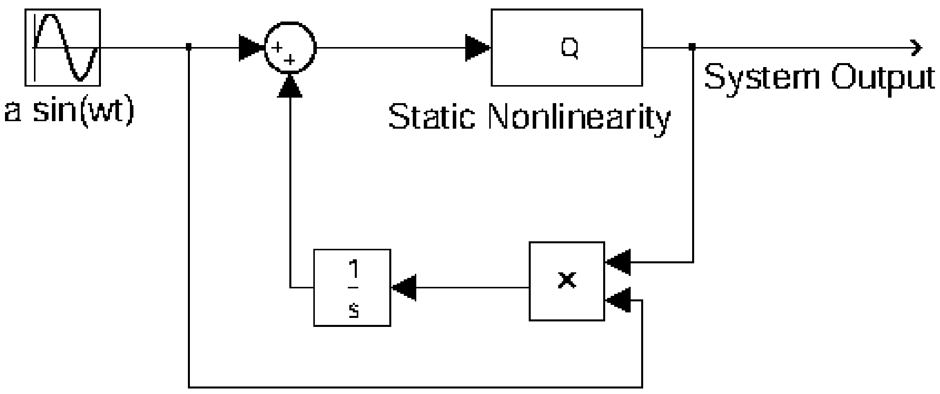
Mean=0.16 m/s (σ=0.08 m/s)

- **Transition Time**

Mean=3.23 ms (σ=0.04 ms)

- **Factor of 6 reduction in impact velocity**

Extremum Seeking Controller



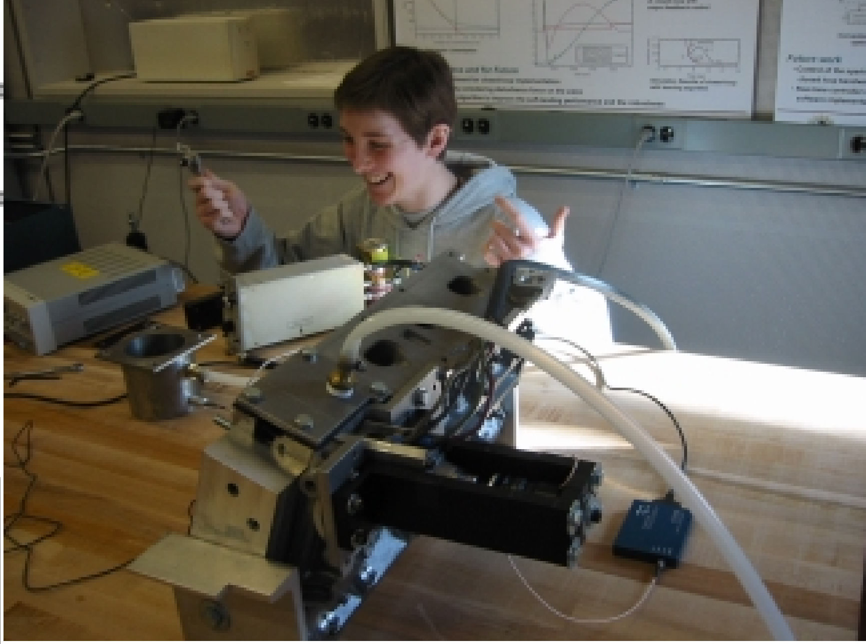
- Extremum seeking control is used to drive the output of a static nonlinearity to a local maximum or minimum

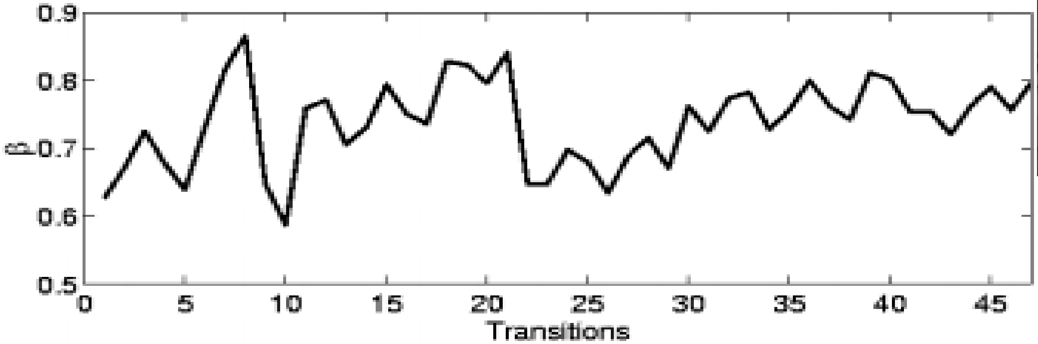
- The system can be treated as a static nonlinearity by viewing
  - The parameter β as the input
  - The function:

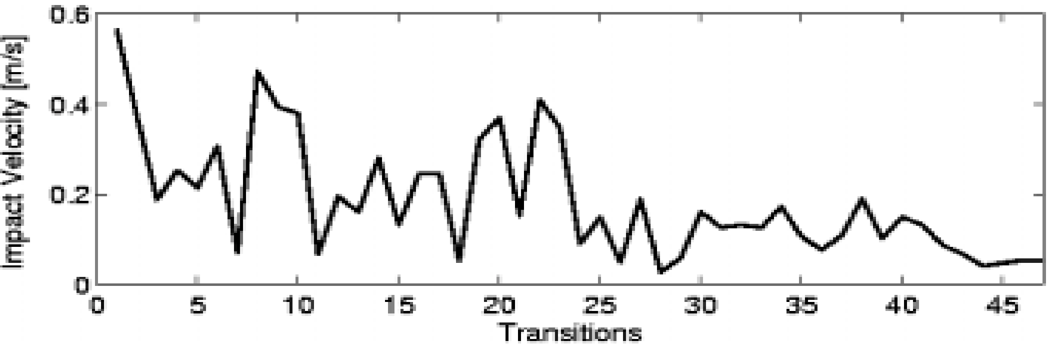
    $(0.05 - v_I)^2$

    as the output

Experimental Results





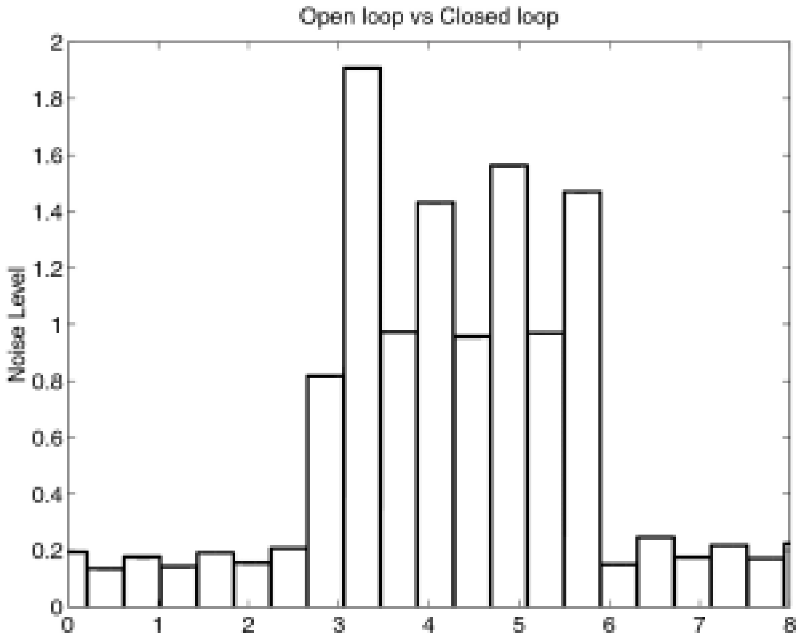


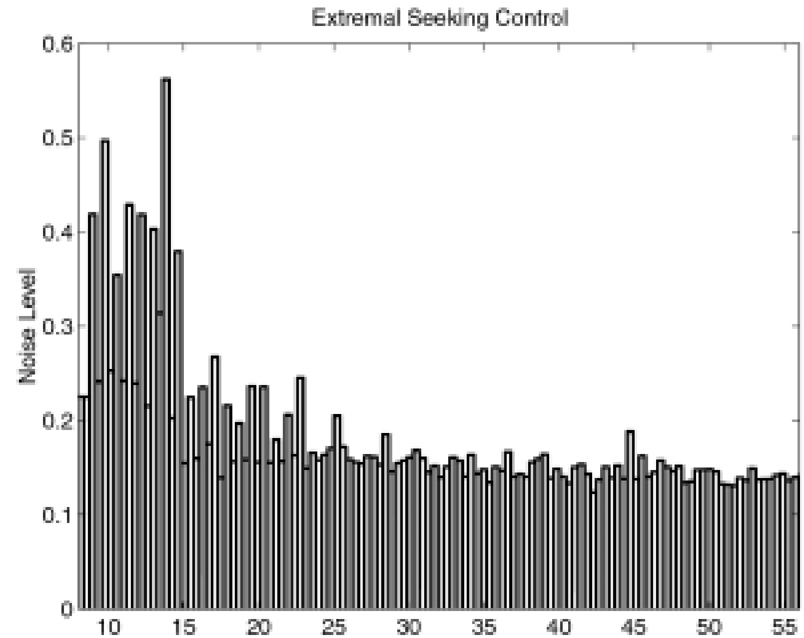
Impact Velocity

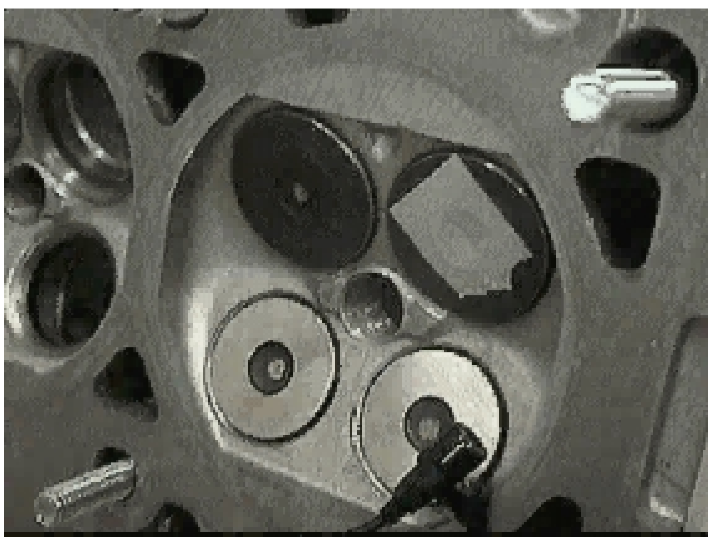
- **Mean: 0.08 m/s**
- σ: 0.05 m/s

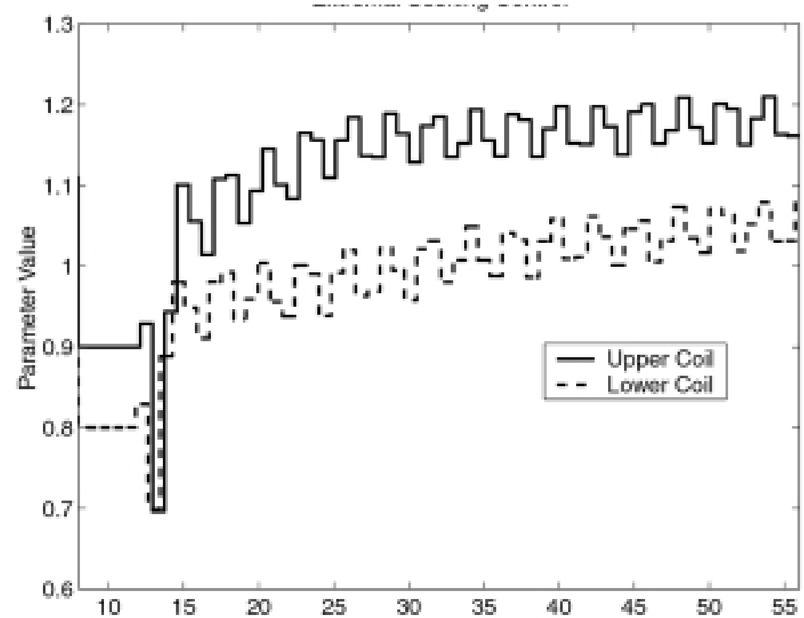
Additional factor of 2 reduction

- **Total of a factor of 12 reduction!!!!!**









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Conclusion and Future Work

- Conclusion:
  - A nonlinear controller were designed and implemented
    - Achieved a mean impact velocity of 0.16 m/s
    - Achieved consistent transition times of less than 4 ms
    - Factor of 6 reduction over open loop control
  - Extremal Seeking Control was applied to improve performance from cycle to cycle
    - Achieved a mean impact velocity of 0.08 m/s
    - Factor of 12 reduction over open loop control!!!!!

- Future Work:
  - Study the affects of valve lash
  - Augment controller to account for disturbances caused by pressure differences across the valve

The question at hand: Will this control algorithm make camshafts obsolete??