Mechanical Characterization of Fuel Injector Piezoactuators and Their Piezoceramics

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The Following Will Be Presented

• Background
  – Goals
  – Why piezo multilayer actuators (MLAs) for fuel injectors?

• Testing (Micro and Macro)
  – Piezoceramic - effect of E field on mechanical strength
  – Piezoactuator - changes in displacement and strain

• Summary

• Future work
Several Motivations Drive This Project

• HVPM Program seeks more precise spray control of fuel injectors - MLAs an enabler

• Piezo MLAs can reduce NO\textsubscript{x}, particulates, fuel consumption, and engine noise

• At issue - PZT actuators susceptible to electromechanical fatigue and are brittle; adapt structural ceramic design methods

• Evaluate MLA reliability under representative service conditions

• Link constituent micromechanical and MLA macromechanical responses
Piezoactuation in Fuel Injectors Has Advantages

**Solenoid actuation**
- Limited to binary response
- Controls fuel quantity well but limits flow rate profile control

**Piezo actuation**
- Enables rate shaping
- Controls both injection timing and fuel quantity control

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- **Crank Angle (deg)**
- **Injected volume per stroke**
  - Main
  - Pilot
  - Timing
  - Shaping
Piezoceramic Characterization:
Part 1 of 2

Testing of stand-alone PZT layers
Effect of E Field on Mechanical Strength (4 Cases)

[1] Open circuit & “+” electrode in tension

[2] Electric field & “+” electrode in tension

[3] Open circuit & “−” electrode in tension

[4] Electric field & “−” electrode in tension

Ball-on-ring configuration, 2 mm steel ball diameter, steel supporting ring 7.4 mm ID, specimen = 10 x 10 x 0.273 mm, applied voltage 327 V or $E_{\text{applied}} = E_c = 1.2 \text{ kV/mm}$
Electric Field Affects Mechanical Strength

Surface-located defects were the strength-limiters

Characteristic Strength, $\sigma_\theta$, (MPa)

Weibull Modulus, $m$

Positive &
$E = 1.2 \text{ kV/mm}$

Pooled
Negative & Positive
$E = 0$

Negative &
$E = 1.2 \text{ kV/mm}$

± 95% Confidence Ratio Rings

Porous Region

Surface-located defects were the strength-limiters

Surface-located defects were the strength-limiters
Fracture Toughness Dependence on E Field

Fracture Toughness, $K_{ic}$, (MPa$\cdot$m) vs. Flaw Size, $a$ (µm)

- Neg, $E = 1.2$ kv/mm
- Neg, $E = 0$
- Pos, $E = 0$
- Pos, $E = 1.2$ kv/mm

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Piezoactuator Characterization: Part 2 of 2

Testing of entire MLA
Evaluation of a “Plate-Through” MLA

- Configuration (a) is most common but stress concentrations result from discontinuities at ends of electrodes
- Configurations (b)-(e) proposed to resolve stress concentration issue

(Aburatani et al., 1994; Pritchard et al., 2001)
Compressive loading via dead weighting

Load Cell

Semi-articulating Si₃N₄ push rod (2)

Non-contact capacitance displacement gage (2)

Piezostack

Labview test control & data acquisition

High voltage & high frequency amplifiers

Load and displacement signal conditioners
Special Software Enables Test Control, Parameter Monitoring, and Data Acquisition
Static Compressive Stress Affects MLA Response
~ 5% Decrease in Actuator Displacement Response But Polarization Unchanged

Test condition: unipolar sine waveform with 150V amplitude, 50 Hz, and 30 MPa static compressive stress

5 \times 10^8 \text{ cycles} \sim 115 \text{ days}
FEA & PDS of MLA Enables Reliability Prediction and Design Optimization

1/4 Model of MLA

Applied Voltage

Axial Displacements

1st Principal Stresses

Ceramic reliability limited by tensile S1
Summary

• Mechanical test facilities established to enable evaluation of both
  – Piezoceramics (microstructure)
  – Piezoactuators (macrostructure)

• Strength of poled PZT is side dependent with negative side weaker in tension. Surface-located flaws were strength-limiter.

• ~ 5% strain reduction observed during 500M cycles in a PZT MLA with no significant loss of polarization. (30 MPa static compression and unipolar waveform at 150V and 50Hz)

• Reliability of piezoactuators is affected by microstructural and macrostructural flaws and damage.

• Displacement reduction may be due to pinned domain motion.
Future Work and Pursuits

• Actively pursue collaborations with both MLA manufacturers and end users
• Fabricate additional MLA fatigue test frames
• Add environmental testing capability
• Add piezoactuator to load train(s)
• Monitor MLA self-heating
• Add mixed loading capability
• More in-depth FEA and PDS commencement