Mechanical Reliability of Piezo-Stack Actuators
(Agreement 13329)

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This presentation does not contain any proprietary or confidential information.

Outline

- Purpose of work
- Barriers
- Approach
- Performance measures and goals
- Technology transfer
- Plans for next fiscal year
- Summary

Purpose of Work

- Contribute to the attainment of 55% thermal efficiency in HDD engines with concomitant reductions of NOx and PM.
- Develop and exploit advanced fuel injection strategies and adapt them to HDD engines.
- Adapt structural ceramic design methods to the design optimization (i.e., tensile stress minimization) of piezoceramic multilayer actuators (PMLAs).

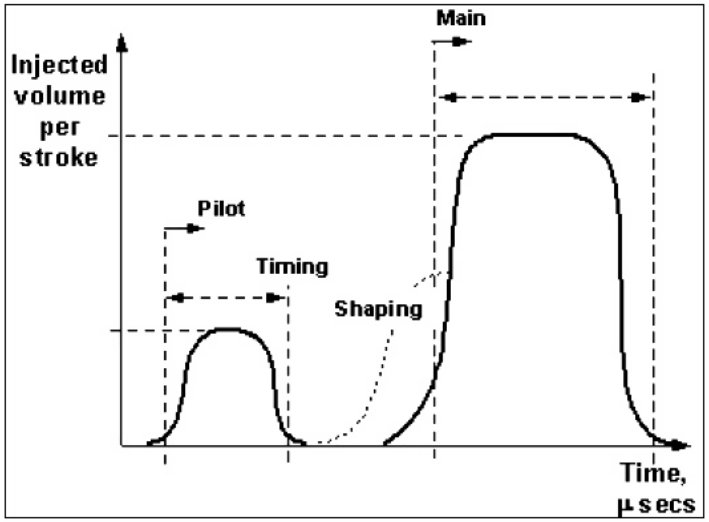
Piezo-actuated fuel injector used in Ford 6.4L Power Stroke® (LDD) engine

Barriers

- Spray control of solenoid fuel injectors imprecise and limited; PMLAs can enable precise and complex fuel injection.
- NOx, PM, fuel consumption, and noise are too high in HDD engines; use of PMLAs in fuel injectors can reduce them all.
- PMLAs can be susceptible to fatigue and are brittle; the successful adaptation of structural ceramic design methods enables their management and predictable lifetime.

Piezoactuation enables:

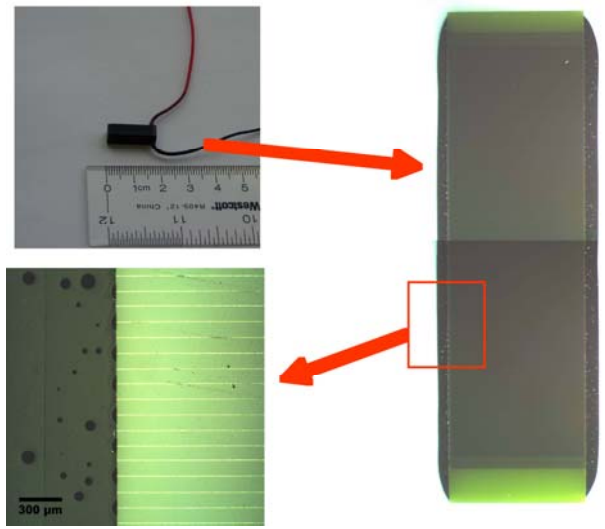
- Rate shaping
- Control of both injection timing and fuel quantity control



Approach

- Measure and contrast mechanical properties of piezoceramics that are candidates for use in PMLAs.
- Measure response and reliability of PMLAs and link to measured piezoceramic properties (microscale/macroscale).
- Develop accelerated test methods that enable rapid and reliable qualification of PMLAs.
- Adapt to fuel injectors for HDD engines.

PMLAs have a macroscale and a microscale



PMLAs would be used inside a fuel injector

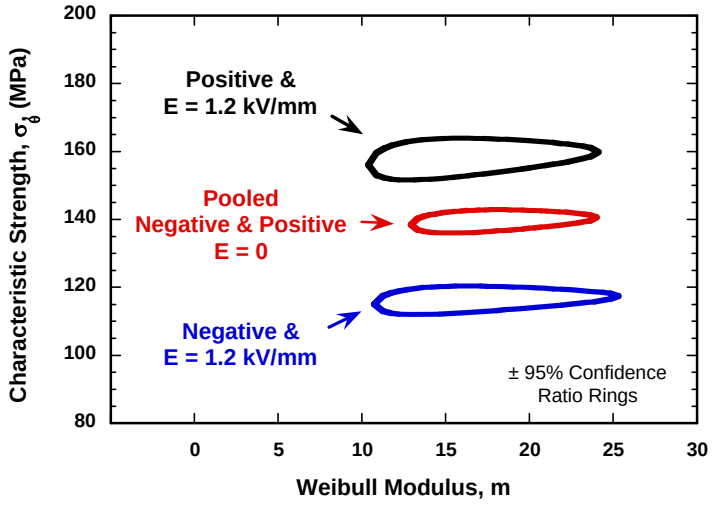
Performance Measures

- Use design sensitivity analysis with a PMLA to increase its survivability by 25% without compromise to needed operational total displacement and load bearing capability.
- Provide strength-limiting-flaw size distribution information to piezoceramic manufacturers to enable process modification that will increase material strength by 20%.

Accomplishments/Progress/Results

- Test facilities established to piezoelectrically and mechanically evaluate piezoceramic materials and PMLAs.
- Effects of electric field on strength of poled piezoceramic.
- Strength-limiting flaw types identified in tape-cast piezoceramics.
- Displacement changes interpreted and fast Fourier transform (FFT) analysis used to study dielectric and piezoelectric constant changes during 10^9 cycle operation of a PMLA.

Electric field affects mechanical strength in poled piezoceramics



Technology Transfer

- An analysis method has the potential to be used with HDD engine fuel injectors to continuously diagnose changes in dielectric, piezoconstant, and displacement of a PMLA, and forewarn of PMLA mortality.
- Information about strength-limiting flaw distributions in commercial piezoceramics can be used by their manufacturers to modify their processing to reduce the maximum flaw size and increase strength.

Activities for Next Fiscal Year

- Develop design sensitivity model for PMLA.
- Further refine analysis of size-scaling and PMLA response and reliability.
- Complete development of accelerated test methods.
- Execute research as part of (anticipated) CRADA with Cummins, Inc.

Summary

- Confident utilization of PMLAs in HDD engine fuel injectors will be enabled and decrease fuel consumption rate.
- Characterizing, modeling, and linking microscale and macroscale performances of piezoceramics and PMLAs.
- Employ design sensitivity analysis with PMLAs.
- Manufacturers of piezoceramics will be able to increase material strength while end-users of PMLAs will be able to diagnose performance changes and predict end-of-life.
- Next year's efforts to include:
  - Study of PMLA performance and size-scaling
  - Completion of accelerated test method development
  - Anticipated CRADA with Cummins, Inc.

Publications, Presentations, Patents

- A. A. Wereszczak, “Mechanical Characterization of Fuel Injector Piezoactuators and Their Piezoceramics,” presented at 13th DEER Conference, Detroit, MI, 16Aug07.
- H. Wang and A. A. Wereszczak, “Effects of Electric Field and Biaxial Flexure on the Failure of Poled Lead Zirconate Titanate,” in review, *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, Dec07.
- H. Wang, A. A. Wereszczak, and H. -T. Lin, “Fatigue Response of a PZT Multilayer Actuator under High-Field Electric Cycling with Mechanical Preload,” in ORNL internal review, Feb08.