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Development of a Smart Materials Actuated Fuel Injector for Automobile Engines

Yoshio Akimune, Tatsuo Sugiyama, Kazuo Matsuo, Junko Iita
Smart Structure Research Center, AIST
FAX:81-29-861-3126, y-akimune@aist.go.jp
R-J Xie
National Institute for Materials Science
FAX:81-29-851-3613, XIE.Rong-Jun@nims.go.jp

Abstract

This report concerns the development of a piezoelectric actuator for driving a fuel injection valve to be used in an automobile engine of stratified combustion system. The experimental actuator consists of a stack of piezoelectric disks, measuring 60 mm in total length. In this actuator, with a displacement loop of 500 V and 27 μm in the voltage-displacement curve, the ratio of maximum differential displacement to maximum displacement was 26 %, and the compressive displacement for 30 MPa was 100 μm or greater with 500 V applied. With an actuator of such a performance, a fuel injection valve for an automobile engine of response time 0.1 ms or shorter was successfully manufactured on trial basis.

Key words: Fuel Injector, Piezoelectric Ceramics, Automotive, Engine, Smart Materials

1. INTRODUCTION

Recently, a lot of efforts have been made for R&D of automobile engines based on in-cylinder direct fuel injection system in place of natural aspiration, because of increased recognition of better mileage and reduced emission of pollutant gases in the former design. Consequently, major auto manufacturers of Japan, such as Mitsubishi Motors Corporation [1], Toyota Motor Corporation [2], and Nissan Motor Co., Ltd. [3], are putting direct injection gasoline engines into the market.

In the engine of in-cylinder direct gasoline injection type, atomized fuel is directly fed into the cylinder in the compression stroke. In most of these engines, the piston crown is fabricated into a specific curved face adapted to the combustion pattern, based on the literature [4]. The implementation of such a design is backed by the improved electronic control of fuel supply and the progress in pressurized fuel injection.

There are two patterns of combustion following the spark ignition of fuel directly injected into the cylinder: homogeneous and stratified. In the former mode, fuel is injected and compressed in the in-take stroke, while in the latter, air is taken during the in-take stroke and fuel is injected in the compression stroke.

The injection valve in the engines

referred to above [1-3] is of solenoid type, with the injection pressure set at around 7 MPa, higher than the pressure in the compression stroke. However, the operation of a solenoid valve takes a few ms, fairly longer than the injection time of an ideal compression stroke, leading to a failure of stratified combustion. Hence, the improvement of injector drive for quicker actuation is urgently needed.

To meet such a requirement, two types of actuator materials are currently under development: piezoelectric and magneto-strictive. Both of them are inadequate, because the former has sufficient response rate but fails to provide substantial displacement, while the latter involves problems in response and driving coil.

In the present paper, the development of a fuel injector based on piezoelectric actuator of stacked construction, with a number of piezoelectric stacks, as a means for solving the problem of insufficient displacement will be reported. The actuator is expected to implement a practicable fuel injector for stratified combustion (Fig. 1).

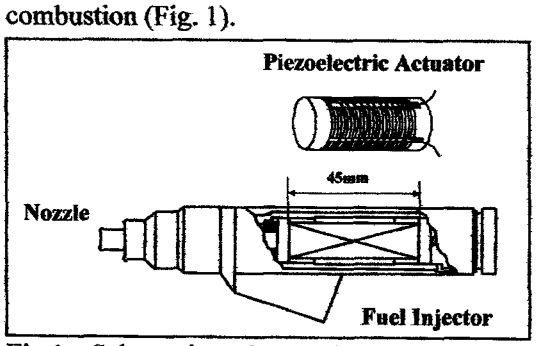


Fig.1 Schematic view of a Piezoelectric Actuator and a Fuel Injector

2. TRIAL MANUFACTURE OF PIEZOELECTRIC ACTUATOR

2.1. Piezoelectric Materials

Lead zirconate titanate (PZT) is used in the present development. The material was sintered into a cylinder, which was ground to 10 to 13 mm in outer diameter, and sliced into disks of 0.3 to 0.4 mm thickness. The disk was printed with electrodes of silver paste, consisting of silver and glass ingredient, baked on the surface, and polarized by applying 1 kV/mm axially in silicon oil of 80 °C. The joining process of stacked actuator is illustrated in Fig. 2. The disk has the following materials parameters: Curie temperature (T_C) = 503 K, longitudinal piezoelectric constant (d_{33}) = 590 pC/N. Other characteristic values are given in Table 1.

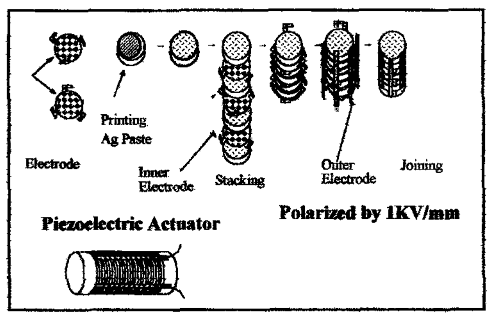


Fig. 2 Joining Process for Piezoelectric Disks

Table1 Material's Parameter

	PZT
d_{33}(pC/N)	590
Kt(%)	65
Kr(%)	70
$\varepsilon_{33}/\varepsilon_0$	1300
t(mm)	0.4
Tc(K)	503

2.2. Construction of Piezoelectric Actuator

The actuator used in the present development consists of 100 PZT disks, specified in Table 1, intercalated with silver electrode films as shown in Fig. 2. The silver electrodes serve alternatively as anodes and cathodes, and the application of voltage across an electrode pair causes dimensional changes in the axial direction. The actuator is provided with end plates of stainless steel (SUS) at both ends, to support the load directly. The ceramic actuator is subjected to load via the metallic end plates practically. The total length of the actuator is around 60 mm.

3. OPERATIONAL CHARACTERISTICS OF PIEZOELECTRIC ACTUATOR

3.1. Static Displacement Characteristics (Voltage-Displacement)

A piezoelectric actuator made of 100 piezoelectric laminates was mounted on a displacement measuring equipment shown in Fig. 3 (total length of ceramics stack is about 45 mm), under a load of 0.1 kN. Alternate voltage of 0.05 Hz varying from 0 to 500 V was applied to the actuator, and its response was monitored with a laser-based displacement sensor. The results are shown in Fig. 4. The actuator gave 27 μm displacement at 500 V. The ratio of maximum differential displacement to maximum displacement in the hysteresis loop of the voltage-displacement curve was 26 %. While the actuator is usually used in combination with a displacement amplifying mechanism, it may be regarded more advantageous to use the displacement directly in view of faster response and greater output force.

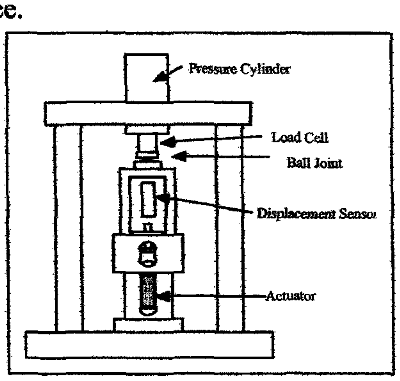
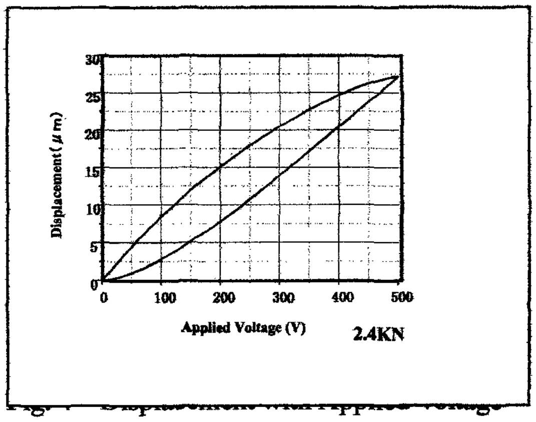


Fig.3 Equipment for Measuring Displacement



3.2. Effects of Initial Load to Voltage-Displacement Characteristics

The relationship of applied voltage to displacement is illustrated in Fig. 5, which is a record of displacement under initial load and following a few cycles of voltage application 0 V → 500 V → 0 V → –500 V → 0 V. The displacement depended upon the initial load: the higher the initial load was, the smaller the displacement tended to become. The displacement at 500 V with initial load 2.9 kN was 33 μm. The difference in maximum displacement between that for voltage change from 0 V to +500 V and that from 0 V to –500 V amounted to around 6 μm in maximum. While the asymmetry may be attributed to a change in materials polarization under stress and domain switching in piezoelectric materials, it seems difficult to make detailed analysis based on crystallographic principle for a stack of polycrystalline disk, not mono-crystalline, actuator. The different absolute values of displacement from that in Fig. 4 may be explained in terms of difference in the method of voltage application. This data has a great significance when utilizing the elongation of stacked piezoelectric actuator with voltage applied under loaded conditions.

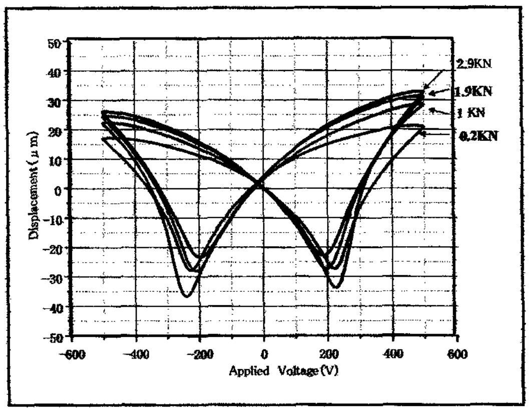


Fig. 5 Displacement with Applied Voltage

The dependence of initial load at 500 V, shown in Fig. 6, presented a peak displacement of 27 μm at 3.43 kN. This may be attributed to the alignment of spontaneous polarization under the initial load of 2~3 kN [6,7].

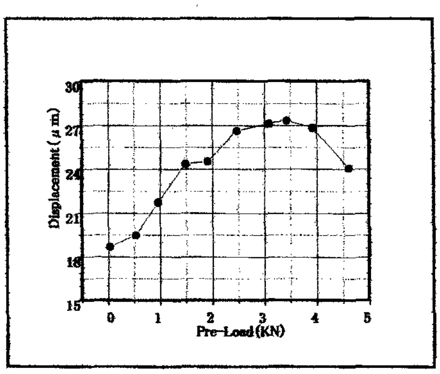


Fig.6 Pre-load Dependence of PZT Actuator

3.3. Load-Displacement Characteristics

In the assessment of load-displacement characteristics, the actuator was applied with a constant voltage and loaded simultaneously. After having applied 500 V to the actuator without pre-loading, and adjusted reading of the displacement sensor to zero, the displacement was measured while varying the load from 0 to 60 MPa (Fig. 7). For a change of stress from 0 MPa to 7.5 MPa, the compressive strain was reduced, with a contraction around 30 μm. As the load was increased, the actuator output began to decline in a non-linear manner [8], reaching to 140 μm in maximum. This data is important for designing a fuel injection valve because additional stress is required in case of applying voltage for the utilization as an injection valve.

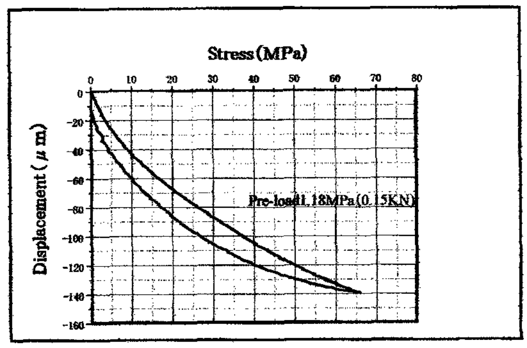


Fig.7 Load displacement under compression.

3.4. Response Time

When a PZT actuator was mounted on a displacement-measuring equipment (Fig. 3) and square wave charge was impressed from the actuator driver with the initial load applied, a quick change in displacement occurred. Under this condition, the behavior of the voltage applied to the actuator and the response for reading the delay time of actuator displacement could be assessed by monitoring the reference signal for triggering the actuator driver, the output voltage of the actuator driver, and the displacement of the actuator (Fig. 8). The response time depended on matching between the actuator and the driver, to be markedly affected by time constant τ, which was determined by capacitance C and resistance R. In the present case, with initial load 1.96 kN and driver output voltage 0 to 500 V, the response time was 0.071 ms.

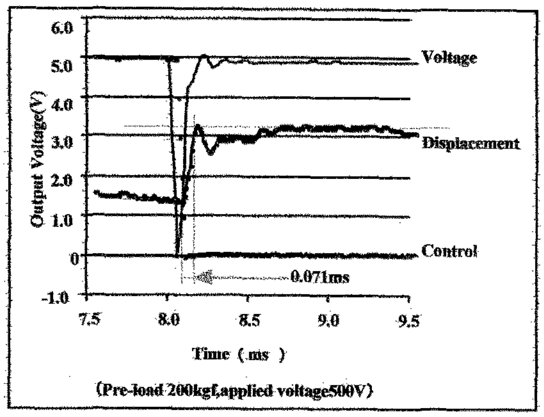


Fig. 8 Response period

3.5. Temperature Characteristics

This paragraph deals with the basic data for ensuring the actuator utilization under the actual engine environment. A mechanism for controlling the actuator temperatures was mounted in the displacement measuring equipment. The temperature control was effected by an oil bath, in which silicon oil was heated and cooled so as to keep the temperature of the immersed actuator could be kept at a fixed level. The actuator temperature was monitored to confirm that the temperatures are stabilized at a prescribed level. Then, the actuator was applied with initial load, the reading of the displacement sensor was set to zero, and the triangular wave of 0.05 Hz frequency was applied with voltage varied from 0 V to 500 V, to read the maximum displacement on the displacement sensor. The maximum displacement was plotted against temperatures in Fig. 9 and the hysteresis changes in Fig. 10. For a range of temperatures from 273 K to 373 K, the displacement increased as the temperature rose linearly. The hysteresis changes were inversely related to the temperatures in contrast to the displacement, while the response time remained unchanged (Fig. 11). On the basis of these facts, it seems necessary to provide a temperature compensation in consideration of temperature dependence in designing an injector, because the heating of actuator through continued operation might cause changes in displacement and hysteresis changes.

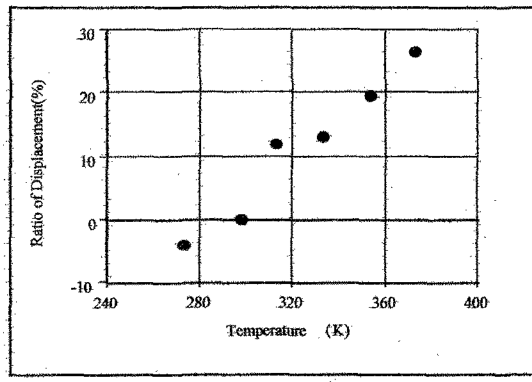


Fig.9 Temperature Dependence of Ratio of Displacement for PZT Actuator

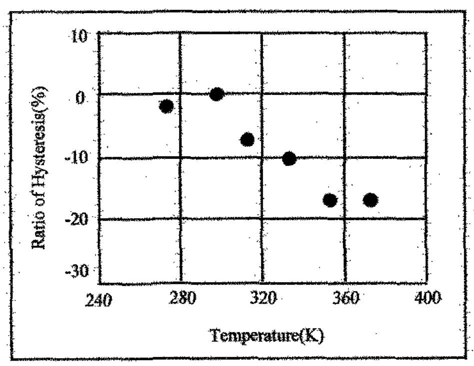


Fig.10 Temperature dependence on Hysteresis for PZT Actuator

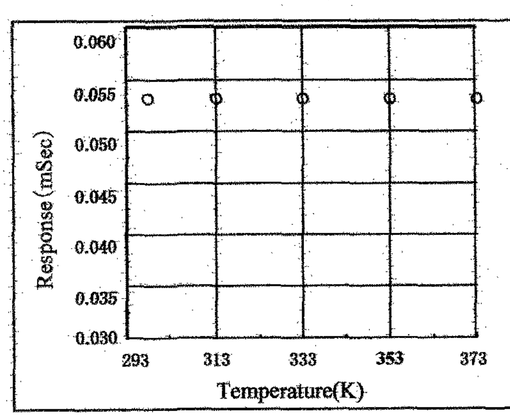


Fig. 11 Temperature dependence on Response for PZT Actuator

4. INCORPORATION to INJECTOR

The total length of the trial-manufactures injection valve with an actuator incorporated was 150 mm. Fig. 12 is a picture of fuel injection from the valve viewed from beneath with 500 V voltage applied at 1 Hz frequency. The injection was effected under the control described in Fig. 7, demonstrating the feasibility of actuator use in the engine. For the application in compact and subcompact cars, it seems necessary, however, to reduce the total length to 100 mm or so for being accommodated in the cylinder head.

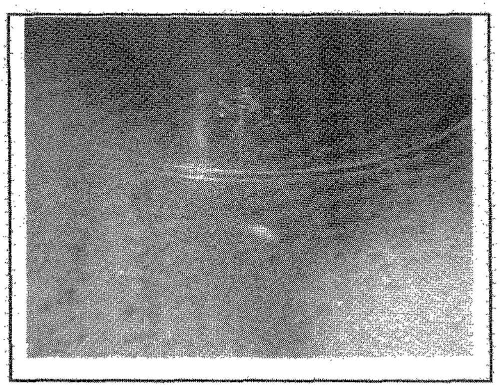


Fig.12 Demonstration of Fuel Injection

5. CONCLUSION

In the present paper, the development of a stacked piezoelectric actuator consisting of PZT laminates was reported, as a means for solving displacement problems inherent to the piezoelectric actuators to be used for driving the fuel injector for the engine of layered combustion type. The stacked construction made it possible to provide greater displacement to the actuator, leading the trial manufacture of an injection valve with response time within 0.1 m·second. The future efforts will be concentrated in the verification of response time and injection pressure with the actuator incorporated to the injector.

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