Design and analysis of piezoactuated micropump for fuel delivery in automobiles

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This study presents piezo actuated valveless micropump, designed for fuel delivery in automobiles, to determine dimensions of piezo actuated micropump, to direct PZT actuated valveless micropump fabrication and to reduce fabrication cost. Complete piezo ceramic actuator is designed and analyzed by using INTELLISUITE software. From simulation results, optimal dimensions of piezo ceramic actuator (diameter and thickness for piezo disc, silicon diaphragm) are selected. This paper also focuses on vibration characteristics of PZT actuator using Thermoelectromechnical analysis.

Keywords: Fuel delivery, INTELLISUITE, Piezo ceramic actuator, Thermoelectromechnical

Introduction

Micro-Electro-Mechanical Systems (MEMS) is integration of sensors, actuators, and integrated circuits on a common silicon substrate with microfabrication technology. Microfluidics deals with design and development of miniature devices, which can sense, pump, mix, monitor and control small volume of fluids. It is an essential part of precision control systems for automotive, aerospace and machine tool industries¹. Core element of microfluidic system is micropumps. According to MEMS, miniaturized pumping devices fabricated by micromachining technologies are called micropumps. In general, micropumps can be classified as mechanical or non-mechanical based method, by which kinetic energy is obtained to drive fluid flow². Mechanical micropumps have been developed using several actuation methods³ (piezoelectric, electrostatic, thermopneumatic, shape memory alloy, bimetallic etc.). Piezo actuated valveless micropumps (PAVM) have simple structure, no internal moving parts, longer life with high efficiency, respond quickly and there is no valve clogging. Stemme et al⁴ presented first piezo actuated valveless diffuser micropump. Development of micropump⁵⁴³ has been expanded for application in wide varieties of fields such as chemical analysis, biological and chemical sensing, drug delivery etc. (Table 1). Cheng et al⁴⁴ proposed thermal bubble micropump on motorcycle fuel atomizer, which is installed on upper end of intake manifold and 20 cm away from engine. It could reduce fuel consumption and improve waste gas emission.

Piezo direct injection (PDI) offers greatest possible fuel savings throughout an extended engine operating range by facilitating stable lean combustion in stratified operation. Compared with a conventional port injection, PDI helps reduce fuel consumption by 20%. Solenoid direct injection (SDI) system is a cost effective solution offering significant opportunities to save fuel, reduce emissions and boost torque at lower engine speeds compared to port injection systems⁴⁵. Recent research in development of piezo-driven valveless micropump has found that a flow rate varying from 42 µl/min to 1.8 l/min is possible¹. This enhances possibilities of using micropump for fuel injection system in automobiles.

With MEMS as driving constituent of recent technoeconomy, this study aims at feasibility study on piezo-driven micropump for fuel delivery in automobile.

Experimental Section

Modeling of Actuator Unit

Model of piezo actuated diffuser valve micro pump (Fig. 1) consists of diffuser/nozzle element, inlet/outlet holes, glass packaging and silicon membrane, which is actuated by a single layer disc type piezo ceramic actuator bonded to membrane. Pump utilizes reciprocating motion
of a membrane actuated by a piezo disc, to induce pumping action. To direct flow, diffuser and nozzle elements are used. Output flow rate of micropump is mainly dependent on maximum displacement of PZT actuator (Fig. 2), which consists of three layers: top, PZT disc; middle, bonding layer; and bottom, silicon diaphragm. When input voltage is applied between top and bottom surfaces of piezoelectric ceramic layer, PZT actuator causes a deformation in entire structure. To find displacement in piezoelectric actuation, modeling and simulation of piezo ceramic actuator is done by using software package INTELLISUITE, which is specifically created for MEMS design, simulation and optimization. Analytical formula that describes static deflection of piezoelectric structure under a certain driving voltage for diaphragm deformation is given as \( \text{Table 1—Characteristic of piezoelectric actuated micropump} \)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Voltage V</th>
<th>Frequency kHz</th>
<th>Flow rate ml/min</th>
<th>Pressure head kPa</th>
<th>Pumping medium</th>
<th>Applications</th>
</tr>
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<td>Gerlach et al.</td>
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<td>5</td>
<td>0.3</td>
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<td>methanol</td>
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<td>Wang et al.</td>
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<td>0.36</td>
<td>-</td>
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<td>drug delivery</td>
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<td>Linneman</td>
<td>-</td>
<td>0.22</td>
<td>1.4</td>
<td>1 bar</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Mu et al.</td>
<td>200</td>
<td>1</td>
<td>0.8</td>
<td>-</td>
<td>water</td>
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<td>Wouter et al.</td>
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<td>Ullmann et al.</td>
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<td>0.55</td>
<td>100 ml/hr</td>
<td>1200 mm H2O</td>
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<td>1.2</td>
<td>-</td>
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<td>Nguyen et al.</td>
<td>50</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>water</td>
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<td>10</td>
<td>2 bar</td>
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<td>0.0004/sec</td>
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<td>Junwu et al.</td>
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<td>3.5</td>
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<td>Zhang et al.</td>
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<td>0.025</td>
<td>0.35</td>
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<td>Wang et al.</td>
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<td>Yang et al.</td>
<td>20</td>
<td>85.3</td>
<td>-</td>
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<td>Ma et al.</td>
<td>67</td>
<td>0.21</td>
<td>3.4</td>
<td>1.8</td>
<td>fluid with glucose</td>
<td>transdermal insulin delivery</td>
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<td>Kim et al.</td>
<td>385</td>
<td>0.130</td>
<td>0.323</td>
<td>0.294</td>
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<td>Wei et al.</td>
<td>125</td>
<td>0.25</td>
<td>1.5</td>
<td>78 cm H2O</td>
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<td>0.8</td>
<td>0.4</td>
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<td>Hsu et al.</td>
<td>140</td>
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<td>Chen et al.</td>
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<td>147</td>
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<td>0.132</td>
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<td>Goo et al.</td>
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<td>Guan et al.</td>
<td>30(p-p)</td>
<td>7.5</td>
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<td>Kan et al.</td>
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<td>9.8</td>
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<td>50</td>
<td>0.14</td>
<td>4.4</td>
<td>9.8</td>
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</tr>
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</table>
where \( C_1 = S_{11}^E \cdot E \cdot (1 - \nu_p^2) / (1 - \nu_d^2) \), \( r_d = \) radius of silicon diaphragm, \( r_p = \) radius of piezo disc, \( d_{31} \), \( d_{33} \), \( d_{33} \) = piezoelectric charge constant, \( t_d = \) diaphragm thickness, \( t_p = \) piezo disc thickness, \( t_{dp} = t_d / t_p = \) ratio of diaphragm thickness to piezo disc thickness, \( V_p = \) voltage over piezo disc, \( S_{11}^E = \) elastic compliance, \( E = \) young’s modulus of diaphragm material, \( \nu_p = \) possion ratio of piezo disc, \( \nu_d = \) possion ratio of diaphragm.

\[
X_0 = \frac{(r_d^2 - r_p^2)^2}{t_p^2 \left[ 3 \left(1 - t_d \left(1 + t_{dp} \cdot C_t \right) \right) \right]^{d_{33} \left(1 + t_{dp} \cdot C_t \right)} - 4 \left[ 1 + t_{dp} \cdot C_t \right]} \left[ 1 + t_{dp} \cdot C_t \right]^{d_{33} \left(1 + t_{dp} \cdot C_t \right)} \right] \]

\[
\ldots (1)
\]

Piezoelectrically driven actuator consists of a thin piezo ceramic disc glued onto a thin silicon diaphragm. An electric voltage is applied between silicon diaphragm and upper site of piezo ceramic material. Top layer of piezo disc acts as voltage terminal and silicon disc as ground terminal. Dimensions of PZT actuator should be properly selected, in order to generate required displacement, which could satisfy flow rate requirement in automobile for fuel delivery. Larger diameter with thinner PZT actuators can usually produce maximum displacements; however, overall size of micropump is increased.

Results and Discussion

Measurement of silicon diaphragm deflection is dependent on electric potential, applied to disc. Maximum deflection is in the centre of diaphragm (4.8 μm), where driving voltage is 150V and this deflection gets reduced when position approaches to boundary (Fig. 3). All lateral faces of diaphragm must be anchored and anchored faces have fixed boundary conditions. Direction of diaphragm displacement depends on the direction of applied voltage and PZT polarization. Displacement varies with voltage linearly (Fig. 4). Displacement of diaphragm increases when diaphragm diameter (optimum, 16 mm) is increased and thickness (optimum, 0.1 mm) is decreased (Fig. 5a). When using discrete glued on piezo disc elements with a standard thickness, this model indicates optimal diaphragm thickness (Fig. 5b); for a 0.3 mm thick piezo disc, a silicon diaphragm thickness of 0.1 mm is optimal. Displacement of diaphragm is maximum (Fig. 6) when diaphragm-piezo disc bimorph and radius ratio \( r_{dp} \) is between 0.85
to 0.94 at different input voltages applied to piezo disc. In this study, diameter ratio 0.88 is selected as optimal one. Analytical solutions of displacement at the center of PZT actuator (Fig. 7) agree well with INTELLISUITE software results. For DC actuating voltage (50-150V), error between analytical solution and INTELLISUITE software result is only 6.3%.

Thus higher input voltage to PZT disc can induce greater displacement for diaphragm, and more fluids may flow through micropump. So, flow rate can be adjusted by increasing or decreasing input voltage. Material properties and dimensions of PZT actuator and diaphragm, respectively, are as follows: Young’s modulus E, 6.6, 160 GPa; Poisson ratio $\nu_p$, 0.33, 0.17; Piezoelectric constant $d_{33}$, $370 \times 10^{-12}$ m/V; - ; thickness $t_p$, 0.3 mm, $t_d$.
In order to find flow rate generated by a PZT actuator, stroke volume $V_s$ of pumping chamber can be calculated by Eq. (1). Theoretical maximum change of volume of pump chamber induced by deflection is $V_{stroke} = \pi * X_0 * r_p^2$. Stroke volume, calculated by substituting maximal centre deformation of $X_0 = 4.8 \, \mu m$ into $V_{stroke}$ equation, is $0.74 \, mm^3$. Therefore, flow rate (Q) can be calculated as $Q = V_{stroke} * f * 60 = 4.4 \, mm^3/min$, where f(Hz) is input frequency applied to PZT disc. From this, calculated flow rate (4.4 mm$^3$/min) is higher than required flow rate for fuel delivery in automobile. So, designed PZT actuator is capable of producing required flow rate for fuel delivery system when it is driven by an input signal of 150V.

Fig. 8—Modal shape of piezoelectric actuator for 1$^{\text{st}}$ to 8$^{\text{th}}$ natural frequencies

0.1 mm); radius ($r_p$ 7 mm, $r_d$ 8 mm); voltage range, 50 - 150 V; and density $\rho$, 2,330 kg/m$^3$.
Natural frequency of piezo actuation is one of the most important parameters in design of valve-less pumps since best performance occurs at that frequency. For proposed micropump, first natural frequency of this actuator is 29,441 Hz. Frequency of driving voltage must be less than first natural frequency. Modal number and its corresponding natural frequencies are given as follows: 1, 29441; 2, 61671.9; 3, 62392.9; 4, 101097; 5, 103185; 6, 116907; 7, 148767; 8, 149996; 9, 178441; and 10, 179953 Hz.

Thermoelectromechanical analysis is used to determine vibration characteristics (natural frequencies and mode shapes) of a piezoelectric actuator. A clear bending peak occurs at the center of PZT actuator during first natural frequency (Fig. 8). Bending peak is drifted from center of disc when modal frequency is increased. Exact frequency range of PZT actuator is determined through modal analysis. From this, harmonic frequency points are selected and at the same time harmonic analysis is carried out based on first natural frequency (29 kHz). Maximum harmonic displacement (Fig. 9) at 29 kHz in z direction is 0.99 µm.

Conclusions

Complete design and simulation of piezo ceramic actuator is carried out using microproduct design software INTELLISUITE. Maximum centre displacement of PZT actuator is 4.8 µm when input voltage applied to PZT disc is 150 V. Theoretical value of stroke volume (0.74 mm³) and flow rate (4.4 mm³/m) satisfies flow rate requirement in fuel delivery system in automobiles. First natural frequency of piezo actuator is found to be 29 kHz and maximum harmonic displacement at 29 kHz in z direction is found to be 0.99 µm.

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