

# A PIEZOACTUATED TOOL FEED MECHANISM FOR MICRO EDM

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## 1. INTRODUCTION

Increased demand for Micro Electro Mechanical Systems (MEMS) demands a micromachining technology that can produce the required three dimensional (3-D) shapes on silicon and other conducting materials at a lower cost. Micro Electro Discharge Machining (Micro EDM) is one of the promising micromachining technique where a tool of few tens of micrometer in size is used to fabricate 3-D microstructures on any electrically conducting materials. In Micro EDM, the tool and workpiece which are immersed in the dielectric medium forms the two electrodes of different polarity. A sufficiently small gap is maintained between them and with application of a pulsed voltage, a spark is produced resulting into melting and evaporation of some portion of the tool and the workpiece material.

Tool feed control is a critical requirement in Micro EDM as both workpiece and tool materials are being eroded during machining. Also since the pulse energy provided during machining is of the order of few hundreds of micro joules, a very small gap of the order of few microns has to be maintained between the tool and workpiece to sustain the spark discharges. These requirements of Micro EDM demand for an actuator which can feed the tool at the desired rate as well as can control the tool movement which will avoid the sparks occurring with longer delay time and which can also avoid short circuiting of tool and workpiece. Micro EDM with an inchworm type of tool feed mechanism was developed by Yong L. et al. [1]. This approach involves two clamping mechanisms along with two piezoactuators. Direct mounting of Micro EDM tool on piezoactuator have not been reported. An accurate tool feed control either by modeling the piezoactuator or by incorporating the feed back control is also necessary.

In this research work, a piezoactuated tool feed mechanism is considered for a home made Micro EDM equipment. An advantage of using piezoelectric actuator is that the voltage applied

to the actuator can provide the information about its displacement by accurately modeling the Voltage-Displacement characteristics. One of the difficulties in using the piezoelectric actuators is their hysteresis behavior between the applied voltage and the displacement. In order to reduce the complexity and to reduce the costs involved in implementing the feed back control system, modeling of the piezoactuator is considered to overcome the hysteresis effect.

In Section 2, Micro EDM with piezoactuated tool feed mechanism is described. Hysteresis behavior of the piezoactuator is presented in section 3 and modeling of the piezoactuator is presented in Section 4. Simulation and experimental results are discussed in section 5, followed by the conclusion in Section 6.

## 2. DETAILS OF IN HOUSE DEVELOPED MICRO EDM SET-UP

A prototype Micro EDM is developed in-house incorporating piezoactuated tool feed mechanism as shown in Fig. 1. It consists of a motorized rotary table with an accuracy of  $0.1^\circ$  and two motorized linear stages having positional accuracy of  $1\mu\text{m}$ . This arrangement is capable of fabricating micro channels with

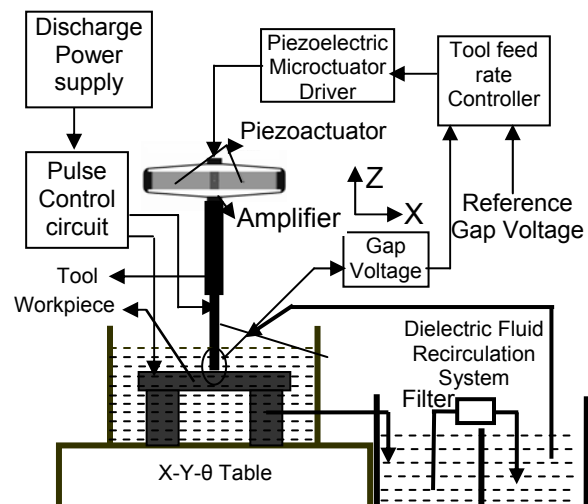


FIGURE 1. Micro EDM Set-up

shapes such as a linear, circular and spiral and fabricating either blind or through micro holes. An in situ measurement technique is used to measure the depth of the blind hole, depth of tool material removed and the total displacement given to the tool by sensing the tool and workpiece electrical contact without disturbing the tool and workpiece set-up.

A piezoelectric micro actuator (Cedrat Technologies, APA400M) is used for feeding and controlling the tool in Z-direction. Two piezostacks are arranged in series and a flexural link is used to amplify the displacement of these two piezo stacks. The maximum displacement of the piezoactuator was measured as 445µm at 150V. The displacement of piezoelectric micro-actuator is controlled by monitoring the gap voltage between the tool and the workpiece. The voltage drops as the spark occurs and correspondingly some amount of material is removed making it an open circuit. Also when it is short circuited, the potential drops to zero. This signal goes from feed back circuit to the piezo amplifier. In this path, the signal is amplified in the feed back circuit by the operational amplifier to make it fall between -1V and 7.5V. The piezoactuator driver further amplifies the signal to 20 times. This amplified signal is directly sent to the piezoactuator which feeds the tool. The tool is fed towards the workpiece until the electric discharge takes place between tool and workpiece. Microstructures with a depth up to 400µm can be machined via the displacement of the piezoactuator.

### 3. HYSTERESIS BEHAVIOR OF THE PIEZOACTUATOR

Piezoactuators exhibit hysteresis behavior between the applied voltage and the

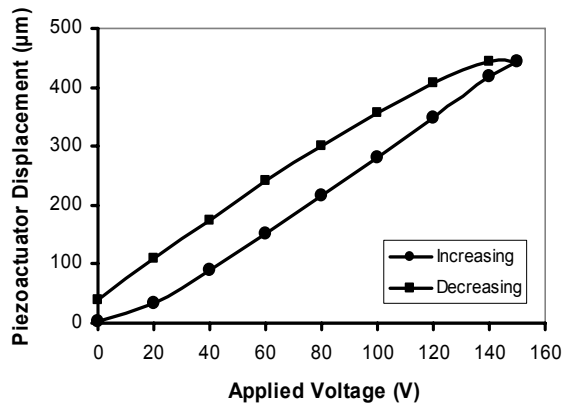


FIGURE 2. Hysteresis Behavior of the Piezoactuator

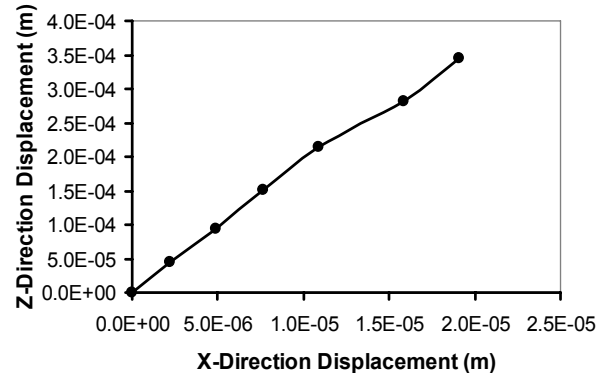


FIGURE 3. Displacement Amplification by Flexural Mechanism

corresponding displacement. Experiments were carried out by varying the input voltage to the piezoactuator. A green light interferometer was used to measure the horizontal (X) displacement and a dial gauge (least count = 1µm) was used to measure an amplified vertical (Z) displacement. Fig. 2 shows the piezoactuator displacement along the Z-direction, indicating the hysteresis behavior when the voltage varied in steps in both forward and reverse directions. The input voltage was varied between 0V to 150V. Fig. 3 shows the amplified displacement in the Z direction by the flexural link for the variation in the piezostack displacement in the X-direction. Since the plot is not linear, a polynomial curve of 3<sup>rd</sup> order is fitted to get mathematical relationship between the X and Z displacements.

### 4. MODELING OF PIEZOACTUATOR

In the present study, electromechanical model for the piezoelectric microactuator is proposed based on [2]. Mechanical and electrical properties of the piezostacks are tabulated in Table 1. The equations (1) and (2) represents hysteresis voltage which is responsible for the hysteresis behavior between the applied voltage and the displacement of the piezoelectric actuator.

$$V_i = \left\{ \begin{array}{l} \left[ \frac{(q - q_h)}{C_i} \text{ if } \left| \frac{(q - q_h)}{C_i} \right| < v_i \right. \\ \left. V_i \text{sgn}(q_j - q_{j-1}) \text{ and} \right. \\ \left. q_h = q - C_i v_i \text{sgn}(q_j - q_{j-1}) \text{ else} \right] \end{array} \right\} \quad (1)$$

$$V_H = \sum_{i=1}^n V_i \quad (2)$$

TABLE1. Parameters Considered For Piezostack Model

| Parameter                         | Symbol     | Value                      |
|-----------------------------------|------------|----------------------------|
| No. of Wafers                     | n          | 200                        |
| Thickness of Wafers               | t          | 0.1mm                      |
| C/S area of Wafers                | A          | 25mm <sup>2</sup>          |
| Relative Permittivity             | $K_{33}^T$ | 2900                       |
| Electromechanical Coupling Factor | $K_{33}$   | 0.7                        |
| Elastic Constant                  | $S_{33}^E$ | 2.22e-11 m <sup>2</sup> /N |
| Mass                              | $m_p$      | 0.00481kg                  |
| Stiffness                         | $K_p$      | 6×10 <sup>6</sup> N/m      |
| Damping                           | $c_p$      | 150 N-s/m                  |
| Capacitance                       | C          | 4×10 <sup>-6</sup> F       |
| Transformer Ratio                 | T          | 14C/m                      |

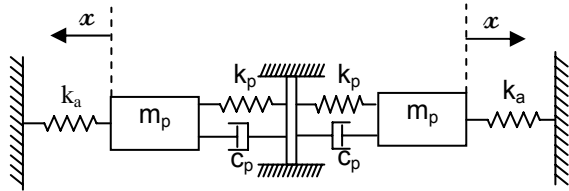


FIGURE 4. Mechanical Model of the Piezoactuator

The piezoactuator has two piezostacks which are modeled as a spring-mass-damper system as shown in Fig. 4. Flexural amplifier is modeled as a spring element and the force generated by this spring element is considered as it opposes the displacement of piezoactuator. Equations (3) to (7) are used for electromechanical modeling of the piezoelectric actuator [2].

$$m_p \ddot{x} + c_p \dot{x} + k_p x = F_t - F_a \quad (3)$$

$$q = Tx + C_p V_t \quad (4)$$

$$V_m = V_H + V_t \quad (5)$$

$$V_H = H(q) \quad (6)$$

$$F_t = TV_t \quad (7)$$

Where

- q = electric charge (C);
- x = piezo displacement (m);
- T = Transformer Ratio (C/m);
- $C_p$  = Capacitance of Piezoactuator ( $\mu$ F);
- $C_i$  = Capacitance of  $i^{\text{th}}$  Maxwell Capacitor ( $\mu$ F);

- $V_t$  = Voltage across Piezoactuator (V);
- $V_{in}$  = Applied voltage (V);
- $V_i$  = Voltage across  $i^{\text{th}}$  Maxwell Capacitor
- $V_H$  = Voltage across Maxwell Capacitor (V);
- $H(q)$  = Hysteresis Function;
- $F_t$  = Transduced force from electrical Domain; (N)
- $F_a$  = Force applied by the flexural amplifier (N)
- $m_p$  = mass of piezoactuator (kg);
- $c_p$  = damping coefficient of piezomaterial (N-s/m);
- $k_p$  = stiffness of the piezoactuator (N/m)

## 5. SIMULATION AND EXPERIMENT

A Matlab-Simulink model is developed for the piezoactuator to obtain the stack displacement for the applied voltage. The stack displacement is converted into the amplifier displacement using the 3<sup>rd</sup> order polynomial equation. Simulations are carried out at different input signals and at different frequencies to investigate the behavior of the developed model. To verify the simulation results, experiments are carried out at various input signals to the piezoactuator. A signal generator (HP 33120A) is used to generate different signal at different frequencies and amplitude of the signal is maintained between 0-6V. This input signal is amplified 20 times by the piezoactuator driver. An inductive pickup is used to sense the displacement of the piezoactuator and the signal generated by this pickup is connected to NI-DAQCard-AI-16E-4 PCMCIA through a NI-DAQ signal accessory. This signal is filtered to reject noise component and is stored into the memory by using NI LabVIEW software. The voltage signal obtained from inductive pickup is calibrated by using the readings obtained from dial gauge with 1 $\mu$ m least count.

Fig. 5 shows the simulated and experimental piezoactuator displacements for 1mHz, 0-120V sinusoidal input. It is observed that the maximum actual displacement reached is very near to the simulated result, but there is an error of about 50 $\mu$ m at valley points. Fig. 6 shows the experimental and simulated displacement readings for 1mHz, 0-120V triangular input signal. This shows an error of 30 $\mu$ m at maximum and minimum point.

Simulation results show an error at zero input voltage which may be due to errors in hysteresis modeling of the piezoactuator. Accurate displacements may be obtained by taking more number of slopes for the initial rising curve in the

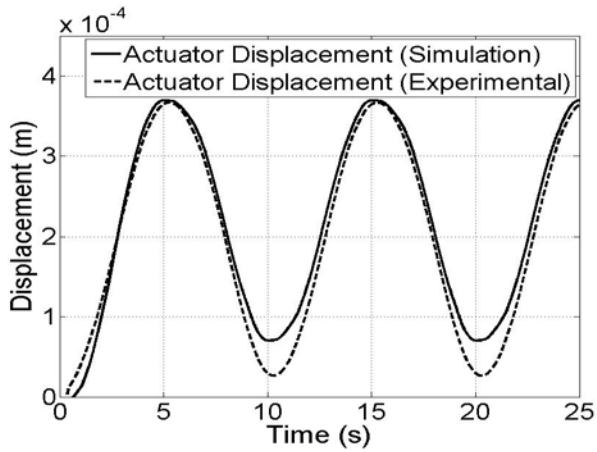


FIGURE 5. Actuator Displacement at 0.1Hz Sinusoidal Voltage Input (0-120V)

hysteresis model. Sinusoidal input voltage signal exhibits better tracking control at peak voltage which may be due to gradual variation of the signal compared to triangular signal input. The errors may also be due to the creep behavior present in the piezomaterial which has not been considered in the model. Errors in calibration of inductive pick-up readings is another source of error for experimental displacement readings.

To investigate the position control of the piezoactuator, a Matlab-Simulink model is developed to calculate the input voltage required for the piezoactuator for the given reference displacement. Fig. 7 shows the reference displacement signal given to Matlab-Simulink model and actual displacement obtained by piezoactuator for the input Voltage signal which is generated by the model. The developed model shows good tracking control at the valley points but it indicates an error of about 50µm at

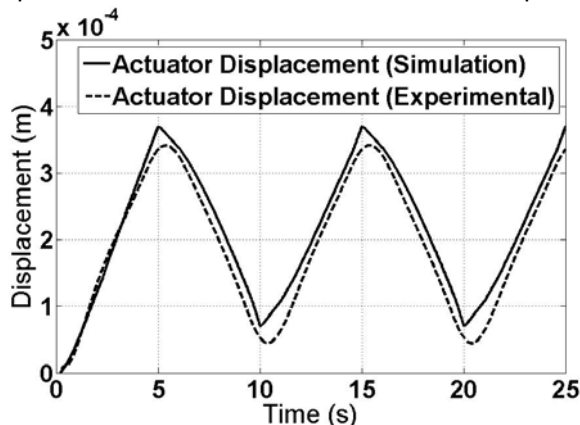


FIGURE 6. Actuator Displacement at 0.1Hz Triangular Voltage Input (0-120V)

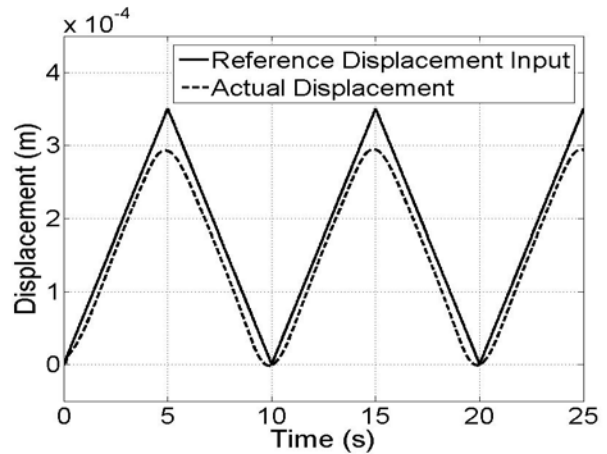


FIGURE.7 Variations in Reference and Experimental Piezoactuator Displacement

the peak points. These errors may be due to the reasons stated earlier.

## 6. CONCLUSION

In this research work, a piezoactuated tool feed mechanism is considered for a prototype Micro EDM equipment. For the tool feed control, a piezoactuator with flexural displacement amplifier is considered and an electromechanical model for this actuator is developed considering hysteresis effect. Simulations for piezoactuator displacement are carried out in Matlab-Simulink and compared with the experimental results. It is observed that, the simulation and experimental results are matching with an error of about 30µm to 50µm at peak and valley points for different types of input signals. These are to be corrected by incorporating creep behavior and by taking more number of slopes in hysteresis modeling of the piezoactuator.

## REFERENCE

- [1] Yong L, Min G, Zhaoying Z, Min H. Micro Electro Discharge Machine with an Inchworm Type of Micro Feed Mechanism. Precision Engineering, Journal of International Societies for Precision Engineering and Nanotechnology. 2002; 26: 7-14.
- [2] Michael G, Nikola C. Modeling piezoelectric stack actuators for control of micromanipulation. IEEE Control Systems. 1997; 17; 3: 69-79.