

# Force Amplification Mechanism for Increased Stroke and Speed Responses of Piezoelectric Stick-Slip Miniaturized Linear Motor

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**Abstract:** In this paper, a mechanical system model based on Simulink software was developed for a proposed design of stick-slip motor. Only the orientation of a cubic PZT element identifies the mode configuration of the motor. The preliminary results showed that force amplification mode exhibited roughly five times more speed, at hundred times more loading force, compared to displacement amplification mode. Interestingly, when the output displacement was compared to maximum expansion of mechanical advantage mechanism, then force amplification mode showed displacement amplification.

**Keywords:** Stick-Slip motor; Piezoelectric motor; Amplification Mechanism; Force Amplification Mechanism; Miniaturized Motor

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## 1. Introduction

Piezoelectric motors are commonly available as ultrasonic, walking and inertia motors [1]. The inertia or the stick-slip motors are commonly applied in positioning applications, where the required actuation force is low if not negligible [1] (pp. 6). The force actuation level depends mainly on the core element of the motor; the piezoelectric material, which is normally available as multilayer stack, made of lead-zirconate-titanate (PZT) ceramics. For example, the commercial PZT stack PA3JEW from Thorlabs Inc. has 360 N blocking force, where the free stroke displacement is 2  $\mu\text{m}$ , which is a 2% of the PZT thickness.

In stick-slip motor, a mechanism holds the PZT element such that long displacement is achieved through accumulation of repeated strokes of the PZT. Motor Mechanisms based on mechanical advantage design exhibits displacement amplification of the PZT stroke, thus enhancing of the motor speed. The structural design of mechanical advantage mechanism can be realized in various forms such as lever [2], asymmetric flexure hinge [3], or oval shell [4, 5]. Lever and flexure hinges designs are fragile mechanisms and require precision manufacturing technology process, especially when miniaturization is a critical application requirement. On the other hand, the shell shape is more compact and reliable design.

Due to the fundamental physics of mechanical advantage, displacement amplification causes definitely a specific force attenuation, which in turn limits the motor capacity in terms of load actuation. For example, the applied PZT stack AE0505D16F from Thorlabs has at 100 V a blocking force of 850 N and free stroke of 11.6  $\mu\text{m}$ . This displacement could be amplified using the asymmetric flexure hinge to a roughly 225  $\mu\text{m}$ , when the motor was loaded by 4.5 N [3] (pp. 6519). The resulting force attenuation in mechanical advantage can be overcome by realizing a larger size PZT stack, however a larger size motor will be produced. In application such as medical implant motor, large force actuation and miniaturized motor scale are required, therefore, the force attenuation due to displacement amplification will be a critical design challenge.

In the following, a new design methodology is discussed as an approach for realizing a stick-slip piezoelectric motor with amplified force and increased stroke actuation response. The

performance of stick-slip motor based on mechanical advantage in Force-Amplification-Mode (FAM) configuration was investigated and compared to the performance of the conventional Displacement-Amplification-Mode (DAM).

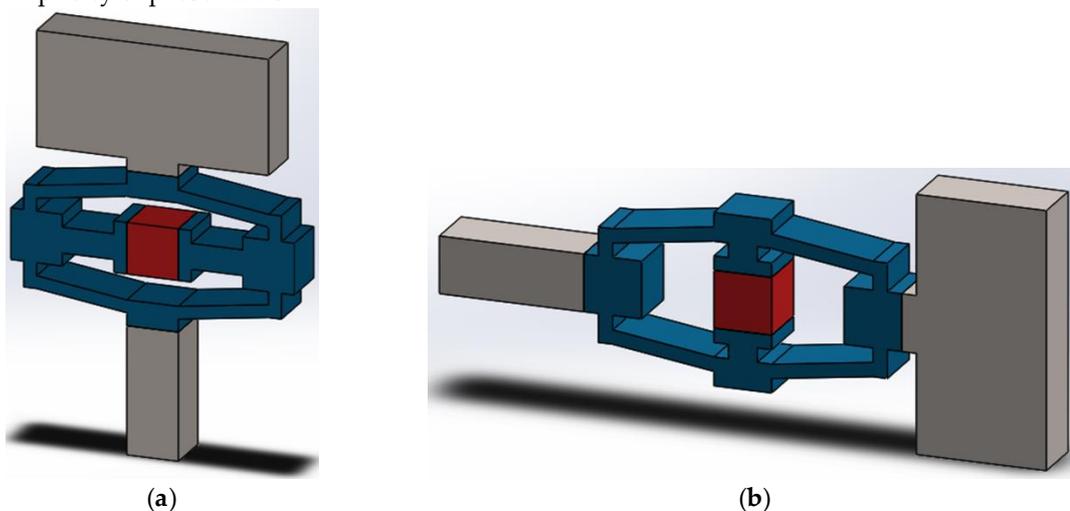
## 2. Methods

### 2.1. New Design Methodology Approach

In stick-slip motor, the total actuated-displacement consists of two components. The first component results due to mechanical expansion of the mechanical advantage mechanism, after the mechanical deformation of the PZT element. The other component is an extended displacement, which results after position-translation of the mechanical advantage mechanism, due to the gained acceleration of the moving slipping mass. This gained acceleration, or the transferred kinetic energy of the moving slipping mass depends on the released elastic energy of the mechanical advantage mechanism, such that, the larger the stored elastic energy, the larger the transferred kinetic energy.

### 2.2. Structural Design

The stick-slip motor consists mainly of piezoelectric actuator, mechanical advantage mechanism, inertial mass, slipping mass and mechanical holder. The displacement amplification mode (DAM) design is shown in **Figure 1a**. The PZT stack is inserted in the center of the folded structure, the mechanical advantage mechanism. The PZT applies forces on the long axis of the mechanism, where inertial mass (large size structure) and the slipping mass (bar structure) are placed at the short axis of the mechanism. The mechanical holder, which holds the sliding mass is not shown in the figure for the simplicity of presentation.



**Figure 1.** Stick-Slip piezoelectric motor design based on: (a) displacement amplification mode (DAM), (b) force amplification mode (FAM).

The force amplification mode (FAM) design is shown in **Figure 1b**. In this mode, the placement of the inertial and slipping masses are reciprocated compared to the DAM design. Also, the applied force of the PZT is on the short axis. In order to apply a reasonable comparison between the DAM and FAM designs, identical dimensions of mechanism and PZT element were considered.

### 2.3. System Modelling and Boundary Conditions

For both DAM and FAM designs, the system can be represented by two coupled oscillating masses as shown in **Figure 2**. The coupled masses and the elastic elements represent the inertial and slipping structures, and the mechanical advantage mechanism, respectively. The common point ( $X_0$ ) between elastic elements is the point at which the PZT element is placed. The points ( $X_i$ ) and ( $X_s$ ) can have different magnitude depending on the oscillation response of the corresponding masses. The displacement actuation is the final value of ( $X_s$ ).

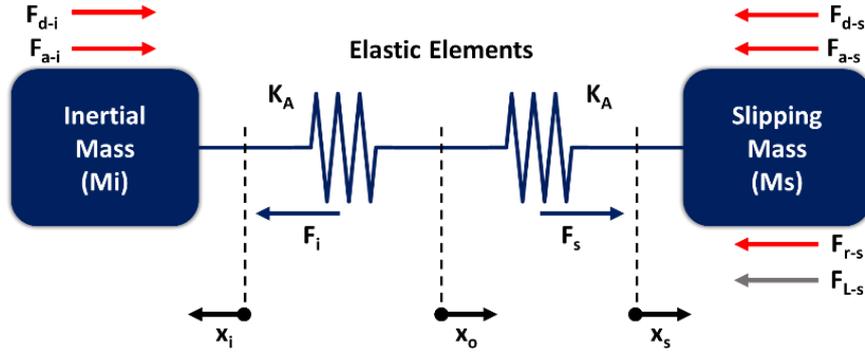


Figure 2. Mass-Spring model of stick-slip piezoelectric motor.

The model is initially set at compressed mode representing the status at which the PZT element is applying actuation force. Therefore, both elastic elements are initially compressed to the maximum actuator displacement ( $S_A$ ), and therefore elastic energy is initially stored in each elastic element. At the moment when the PZT element is switched off, an impulse response is assumed. In this case, elastic energy will be released and appeared as moving masses. In terms of system forces, acceleration, damping and elastic forces will result on each side of the motor; inertial and slipping sides. However, on the slipping side of the motor, further force components were considered. The mechanical friction force due to the mechanical holder effect on the slipping part, and the mechanical loading force due to the actuated object. Assuming neglecting damping effect, the common point ( $X_o$ ) and acceleration of inertial and slipping masses ( $a_i$ ,  $a_s$ ) of the system can be mathematically represented by the following equations:

$$x_o = 0.5 (x_s - x_i), \quad (1)$$

$$a_i = \frac{K_A}{M_i} (S_A - (x_i + x_o)), \quad (2)$$

$$a_s = \frac{1}{M_s} (K_A(S_A - (x_s - x_o)) - (F_r + F_L)), \quad (3)$$

The parameters values of stiffness constant ( $K_A$ ) and initial displacements ( $S_A$ ) of elastic elements depend on the structural design of the mechanical advantage mechanism and the electromechanical characteristics of the applied PZT element. In this work, the focus is on comparing of performances between the DAM and FAM stick-slip motors, regardless of the specific structural design of the mechanical advantage mechanism.

A mechanical advantage mechanism has two ports. An input port where effort is applied and represented by force ( $F_E$ ) and displacement ( $S_E$ ). An output port where the mechanical load is applied and represented by force ( $F_L$ ) and displacement ( $S_L$ ). The mechanical advantage ( $\beta$ ) can be then represented by:

$$\frac{F_L}{F_E} = \frac{S_E}{S_L} = \beta, \quad (4)$$

As stated previously, the input and output ports of the FAM design are reciprocated compared to the DAM design. Therefore, if the FAM design is represented by:

$$\frac{F_A}{F_{PZT}} = \frac{S_{PZT}}{S_A} = \beta, \quad (5)$$

Then the DAM design is represented by:

$$\frac{F_{PZT}}{F_A} = \frac{S_A}{S_{PZT}} = \beta, \quad (6)$$

The Simulink model in **Figure 3** was implemented to extract the system response represented by the mathematical equations above. For this model, a slipping mass ( $M_s$ ) of 0.2 g and inertial mass ( $M_i$ ) of 2 g were considered for both the FAM and DAM designs. The mechanical advantage is 10. A

PZT element with 1.25 μm stroke at 125 N generated force was arbitrary assumed. Accordingly, the  $S_A$  and  $K_A$  values are 0.125 μm and 10 GN/m for the FAM, and 12.5 μm and 1 MN/m for the DAM.

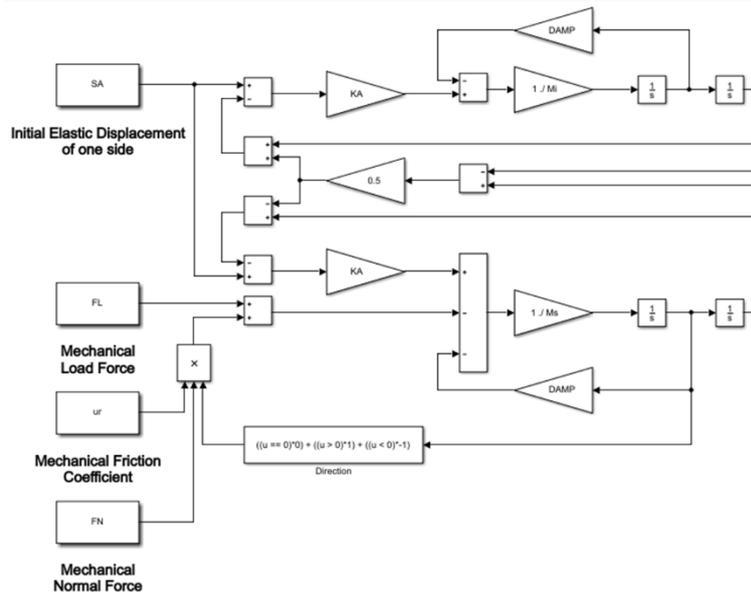


Figure 3. Simulink block diagram of the mechanical model of the stick-slip motor.

### 3. Results and Discussion

The dynamic mechanical response of the FAM and DAM designs in Figure 4a is the resultant displacement of the slipping mass after switching of the PZT element. In this case, the friction force was set to 5 N. In Figure 4b the response was extracted for the FAM design at friction force of 200 N, where the DAM design did not respond at the same conditions due to the too large friction force.

The FAM response shows an impulse response before it goes in steady state. This impulse response represents a displacement amplification due to the accelerated slipping mass. However, due to oscillation the slipping mass return in the steady state to the displacement supplied by mechanical deformation of the elastic element. Such response was not observed in the case of DAM. The velocity of the slipping mass achieved 1.044 m/s at the peak of the impulse in the case of FAM. For the DAM case, no movement was observed at 200 N friction force. However, at 2 N friction force the observed velocity was 0.2263 m/s.

This result should be further investigated to study the effect of applying specific control signal to hold the slipping mass at the peak of the impulse before it decrease down. Also, further design optimization of the inertial and slipping masses might result in further improvement of displacement amplification of the FAM design.

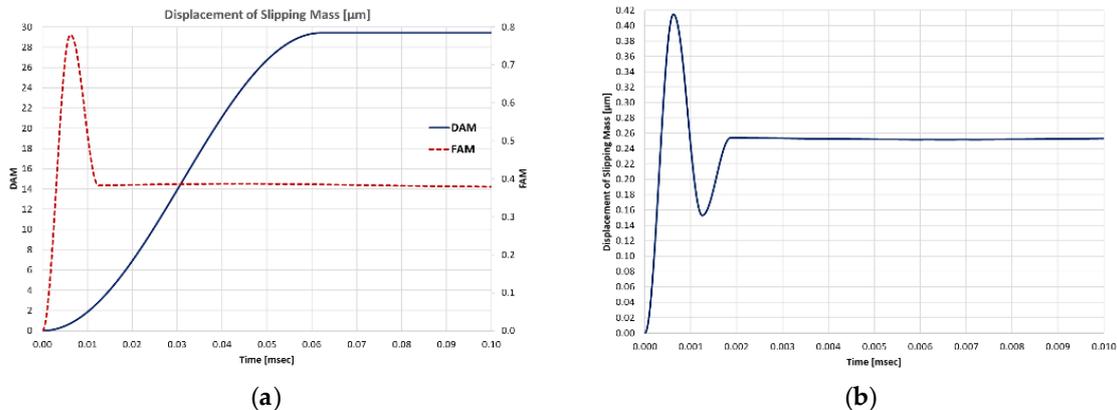


Figure 4. Dynamic response: (a) DAM and FAM responses under friction force of 5 N, (b) FAM response under friction force of 200 N.

#### 4. Conclusions

The force amplification mode (FAM) stick-slip motor has the advantage larger force actuation compared to displacement amplification mode (DAM). In this work, the dynamic response of the FAM showed that due to mass acceleration, displacement amplification is still possible, however before the steady state. Further design optimization of the inertial and slipping mass, and application of specific control signal should be investigated to improve the FAM displacement amplification.

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**Conflicts of Interest:** The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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