

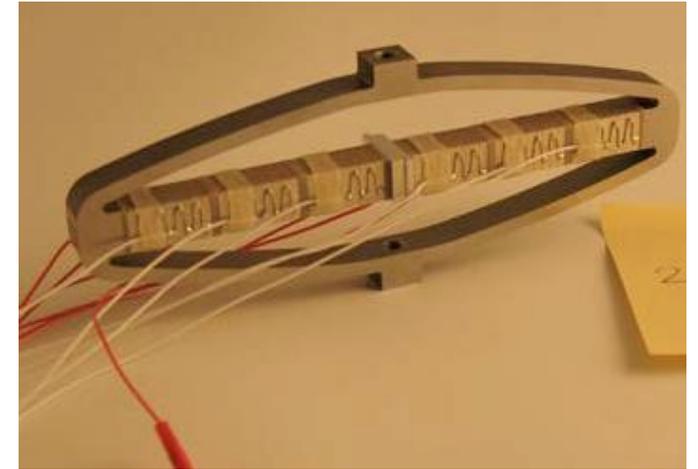
# Force Amplification Mechanism for Increased Stroke and Speed Responses of Piezoelectric Stick-Slip Miniaturized Linear Motor

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## Introduction: Stick-Slip Motors with Amplified Displacement Mechanism

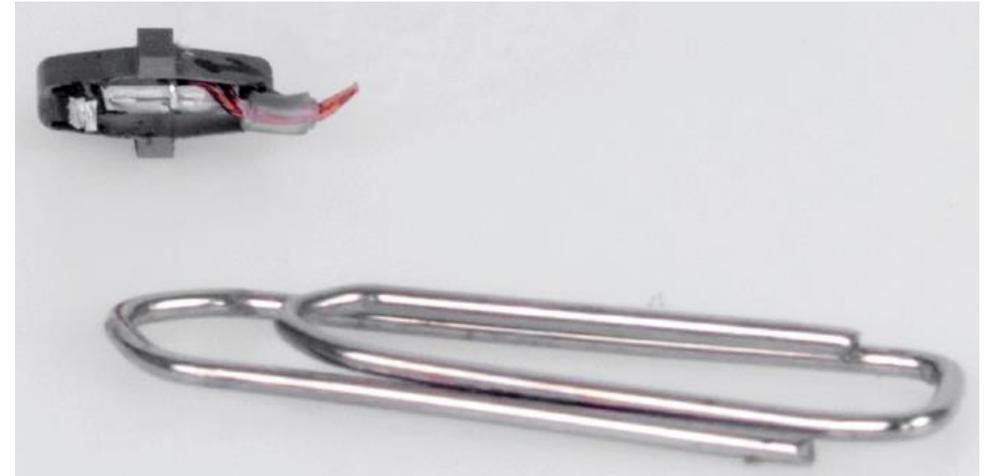
- Piezoelectric stick-slip motors are commonly used in precision positioning applications
- The stroke of stick-slip motor is limited mainly by the piezoelectric actuator deformation response
- Integration of the piezoelectric actuator within a mechanism based on mechanical advantage design will amplify the resultant output stroke
- Mechanical advantage mechanism can be in various forms such as lever supported by a fulcrum or an oval shape structure



Amplified piezo actuator developed by CEDRAT Technologies, short axis is 50mm, long axis is 125mm, thickness is 20mm, total mass is 130g, blocking force is 750N and free stroke is 630 $\mu$ m [M. Ragonet, 2016]

## Introduction: Stick-Slip Motors with Amplified Displacement Mechanism

- For applications such in specific medical implants miniaturization is a critical issue
- Micro piezoelectric motors are commercially available but with also low force actuation capability
- In the example, the micro motor has a blocking force of 1.5 N
- This force limitation might prevent the overall useability of the micro motor in specific medical implants if the required force actuation is much larger



Micro Amplified piezo actuator developed by CEDRAT Technologies, short axis is 3.75mm, long axis is 8.3mm, thickness is 2.5mm, blocking force is 1.5N and free stroke is 39 $\mu$ m [A. Guignabert, 2018]

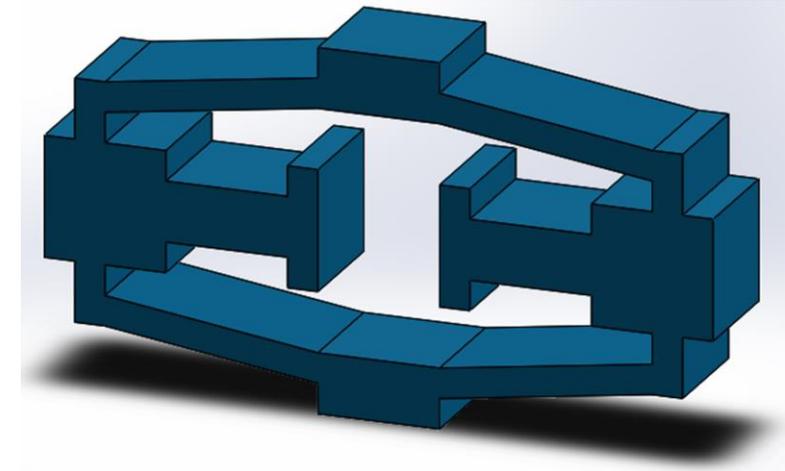
## Objectives

- To develop a mechanical model based on Simulink software for a general purpose mechanical advantage mechanism used in piezoelectric stick-slip motor application
- To investigate by means of simulation the force and displacement actuation responses of piezoelectric stick-slip motor based on amplified displacement mechanism and on amplified force mechanism
- To investigate the possibility of applying amplified force mechanism as alternative approach of amplified displacement mechanism for the piezoelectric stick-slip miniaturized motor

## Methods: Structural Design

- Folded shape mechanical advantage mechanism
- One port (input) for the effort force and displacement ( $F_E$ ,  $S_E$ )
- Second port (output) for the load force and displacement ( $F_L$ ,  $S_L$ )
- Mechanical advantage factor ( $\beta$ ) is represented by:

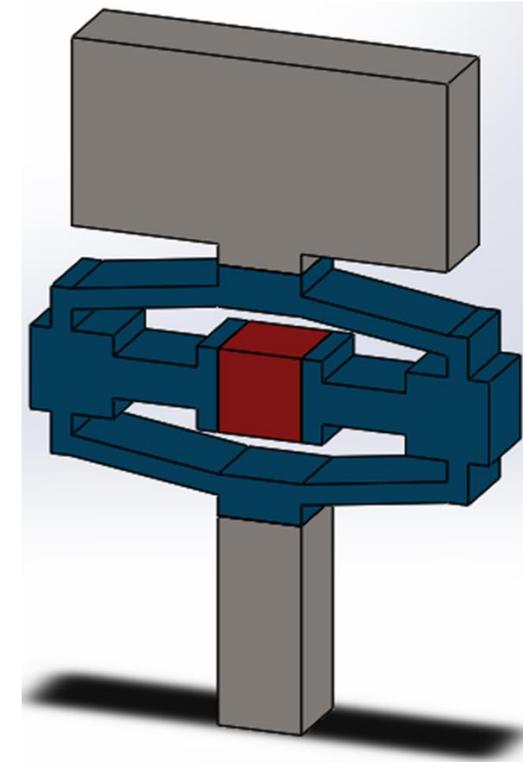
$$\beta = \frac{F_L}{F_E} = \frac{S_E}{S_L}$$



$$F_E S_E = F_L S_L$$

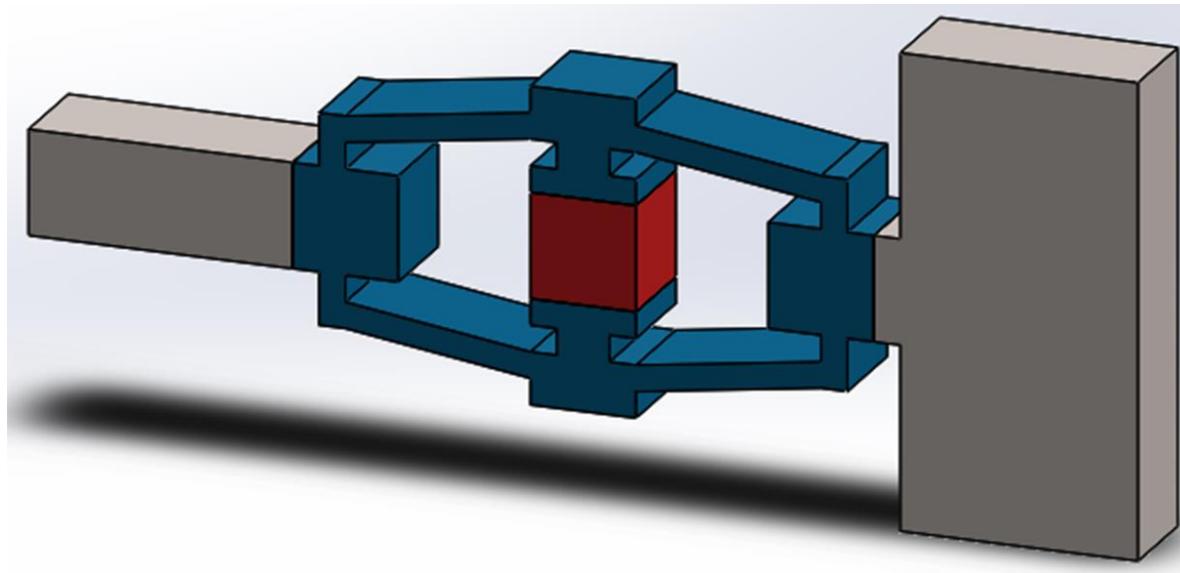
## Methods: Displacement Amplification Mode (DAM) Stick-Slip Motor

- Stick-Slip motor consists of mechanical advantage mechanism, integrated piezoelectric stack, inertial mass, slipping mass and holding mechanism
- The specific dimensions design of the mechanism determine the mechanical advantage factor
- For realizing a displacement amplification mode (DAM) mechanism, the **effort** force should be applied along the **long** axis of the mechanism while **loading** is attached on the **short** axis of the mechanism
- The focus here is on a general purpose mechanical advantage mechanism, therefore the following description is only on the level of designing the mechanical advantage factor regardless of the specific structure design



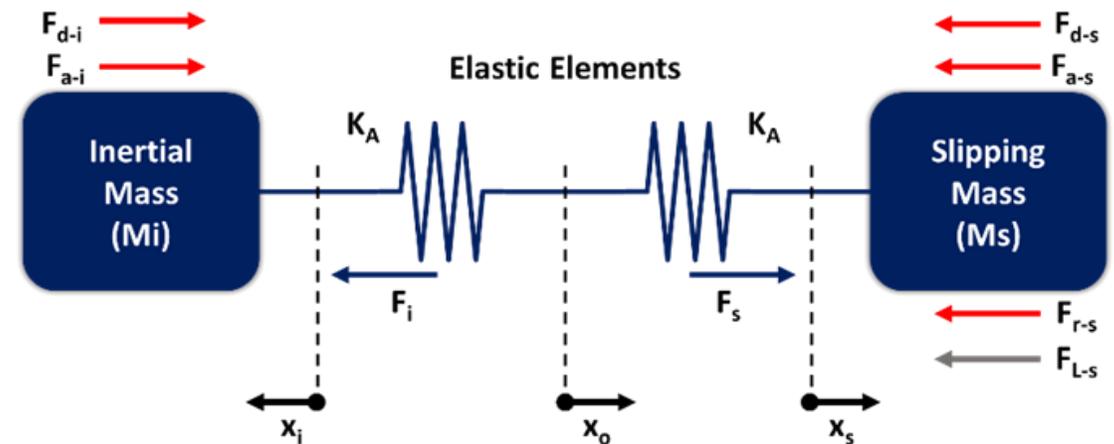
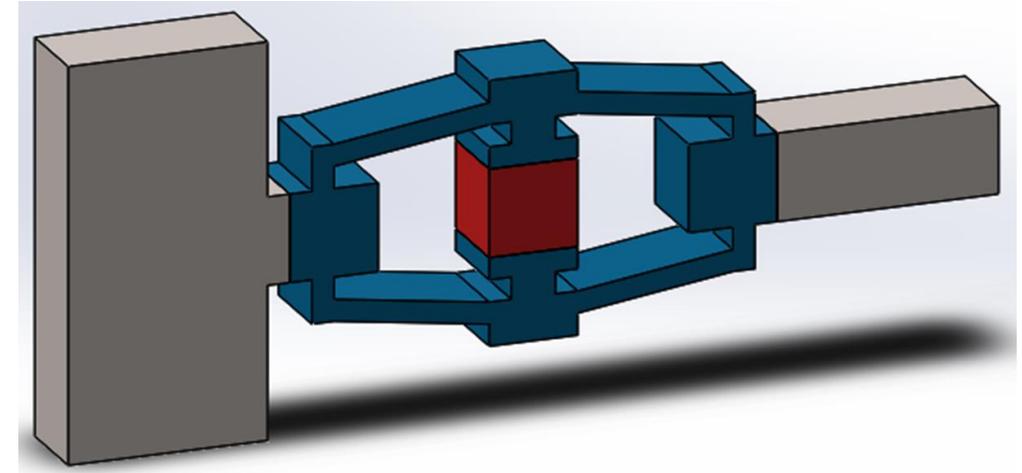
## Methods: Force Amplification Mode (FAM) Stick-Slip Motor

- Alternatively, for realizing a force amplification mode (FAM) mechanism, the **effort** force should be applied along the **short** axis of the mechanism while **loading** is attached on the **long** axis of the mechanism



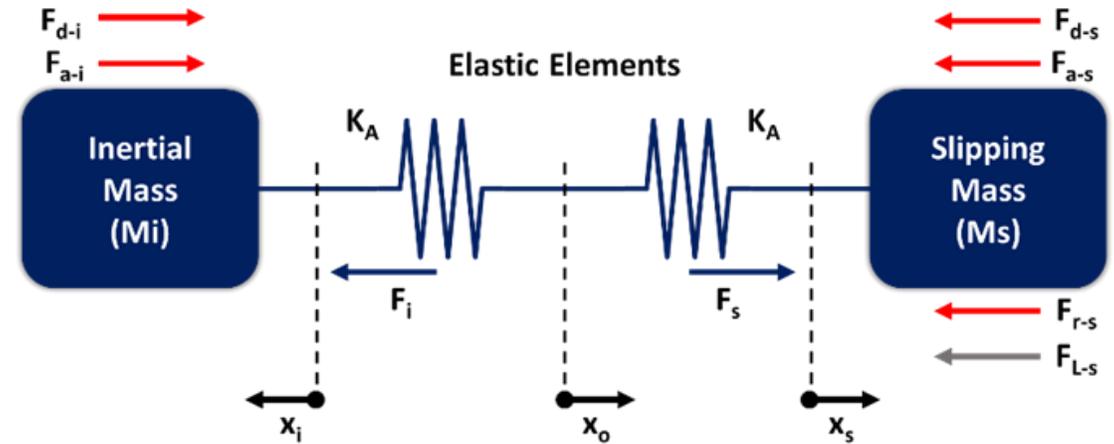
## Methods: Mechanical System Modelling

- The stick-slip motor can be modelled by a two coupled mass blocks
- The model represents the system when it is mechanically pre-stressed (piezoelectric stack is electrically polarized)
- Once the piezoelectric stack is deactivated (assuming impulse response) the stored elastic energy will be released causing mass acceleration



## Methods: Mathematical Modelling

- The two coupled mass system is represented by mathematical equations
- From these equations the dynamic response of inertial and slipping mass components can be extracted under specific initial conditions of mechanical advantage factor and mechanical friction force
- The mathematical equations of the system can be solved by means of Simulink modelling



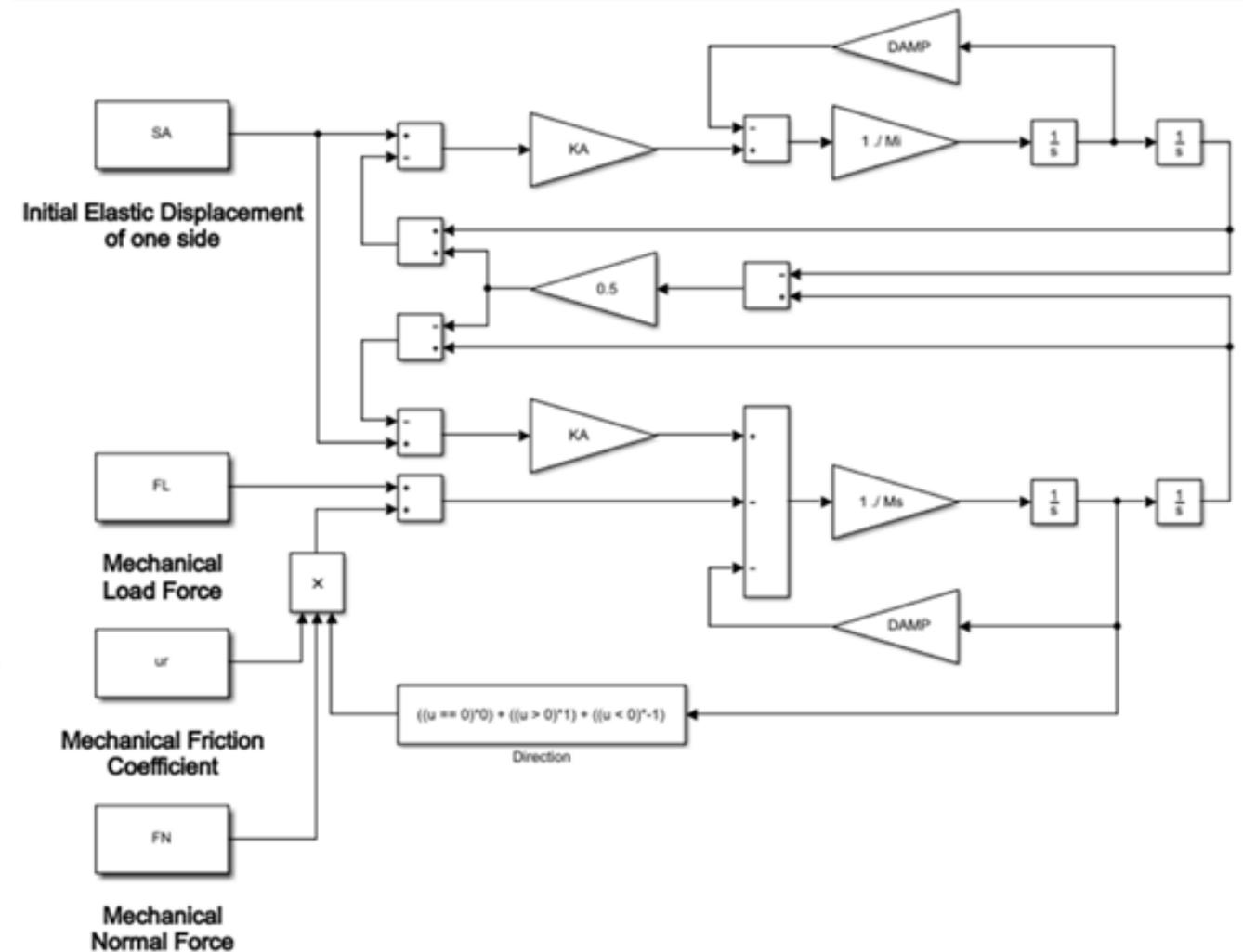
$$x_o = 0.5 (x_s - x_i)$$

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

$$a_s = \frac{1}{M_s} \left( K_A (S_A - (x_s - x_o)) - (F_r + F_L) \right)$$

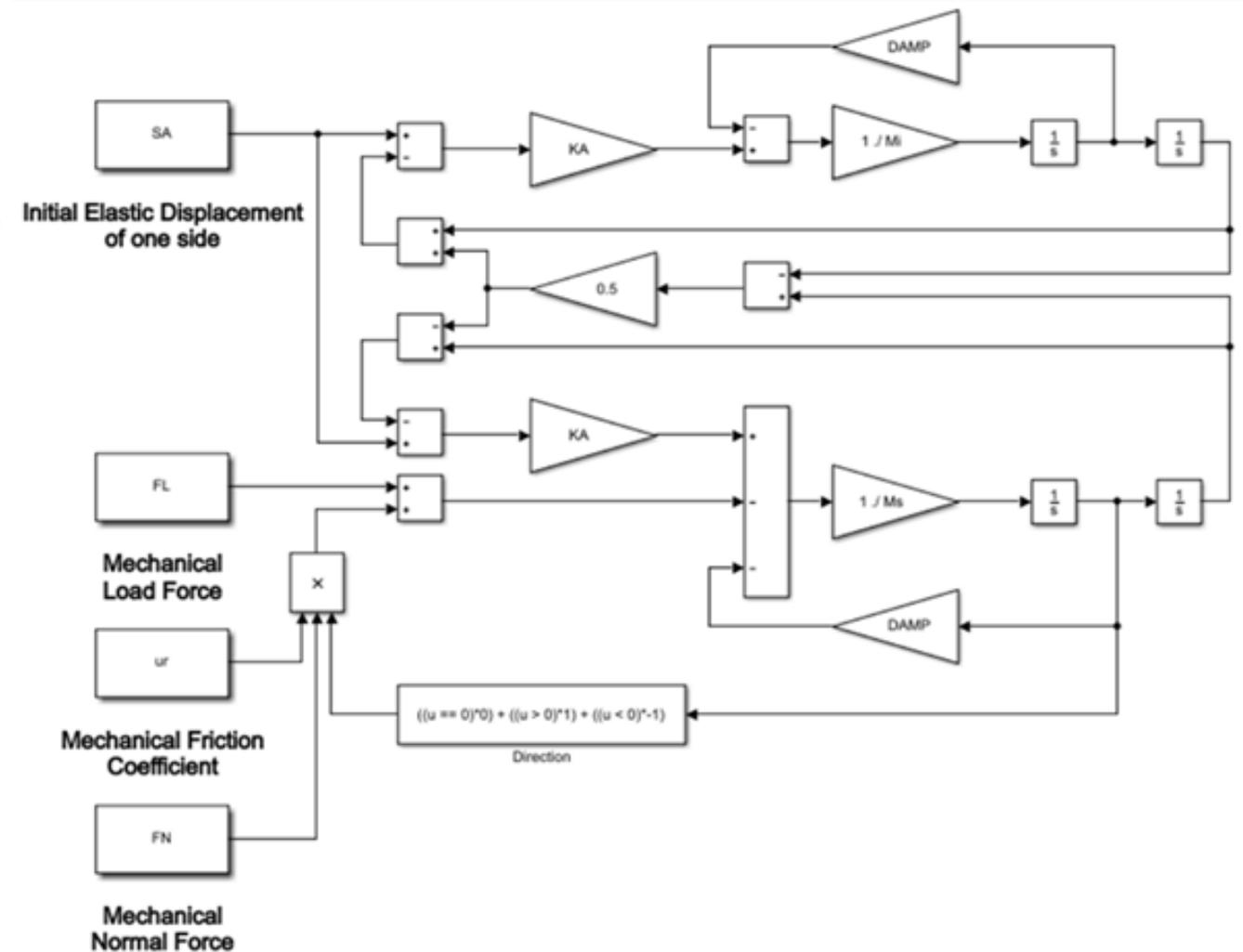
## Methods: Simulink Modelling

- In this model, the inertial mass is 2 g, while the slipping mass is 0.2 g
- A piezoelectric stack was arbitrarily considered such that a stroke of 1.25  $\mu\text{m}$  is generated at 125 N applied force
- For the DAM configuration, the design parameters were calculated such that the stiffness constant of mechanism is 1 MN/m and initially prestressed by 12.5  $\mu\text{m}$



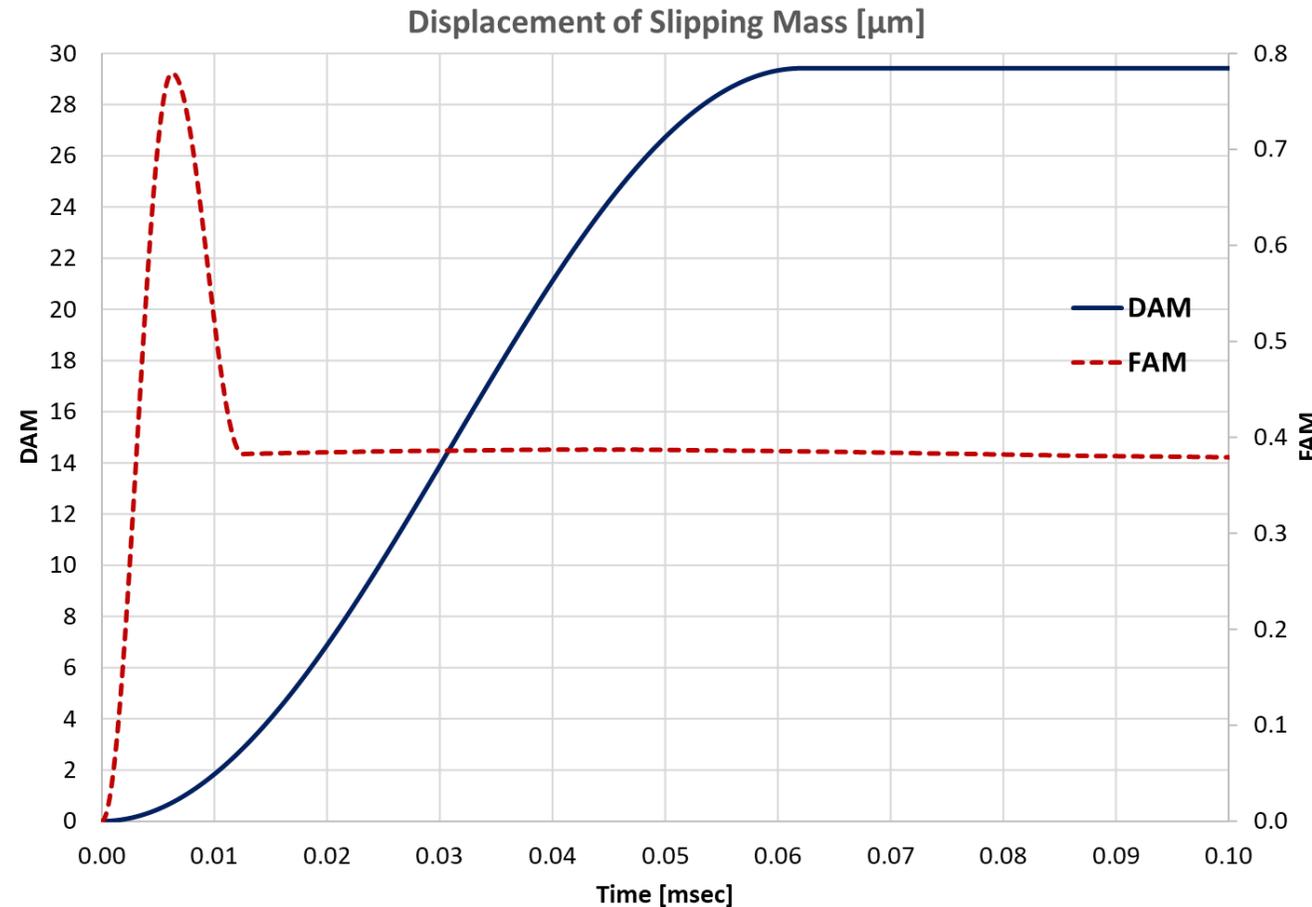
## Methods: Simulink Modelling

- For the FAM configuration, the design parameters were calculated such that the stiffness constant of mechanism is 10 GN/m and initially prestressed by 0.125  $\mu\text{m}$
- The DAM and FAM design configurations were simulated at two mechanical friction force values, 5 N and 200 N



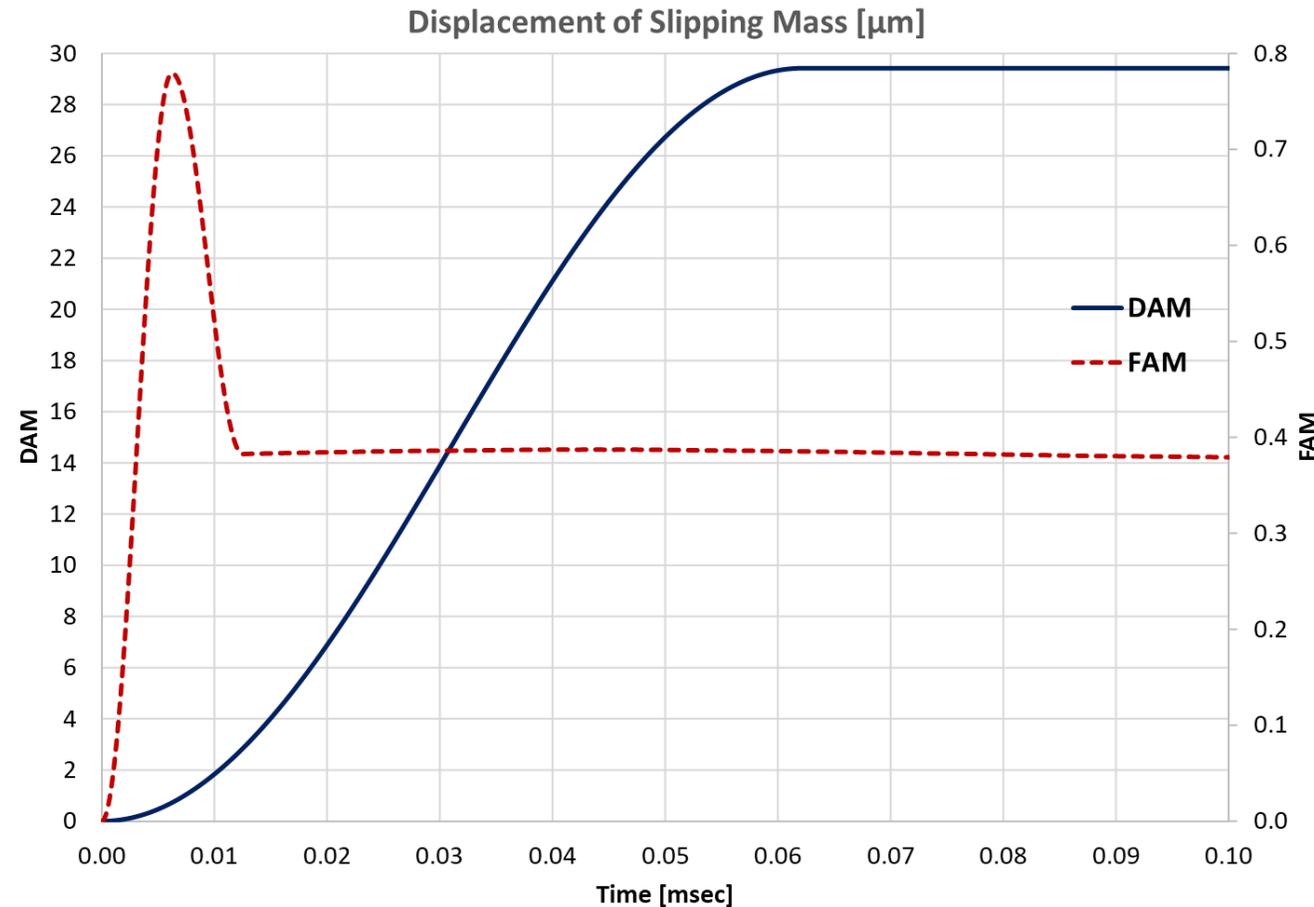
## Results: Displacement Response at 5 N Mechanical Friction Force

- For DAM the possible maximum displacement due to mechanical deformation of the mechanism is  $25\ \mu\text{m}$
- Against a 5 N mechanical friction force, the slipping mass of the DAM achieved  $29.4\ \mu\text{m}$  displacement at steady state
- The extra  $4.4\ \mu\text{m}$  displacement is due to the mechanism translation due to mass acceleration



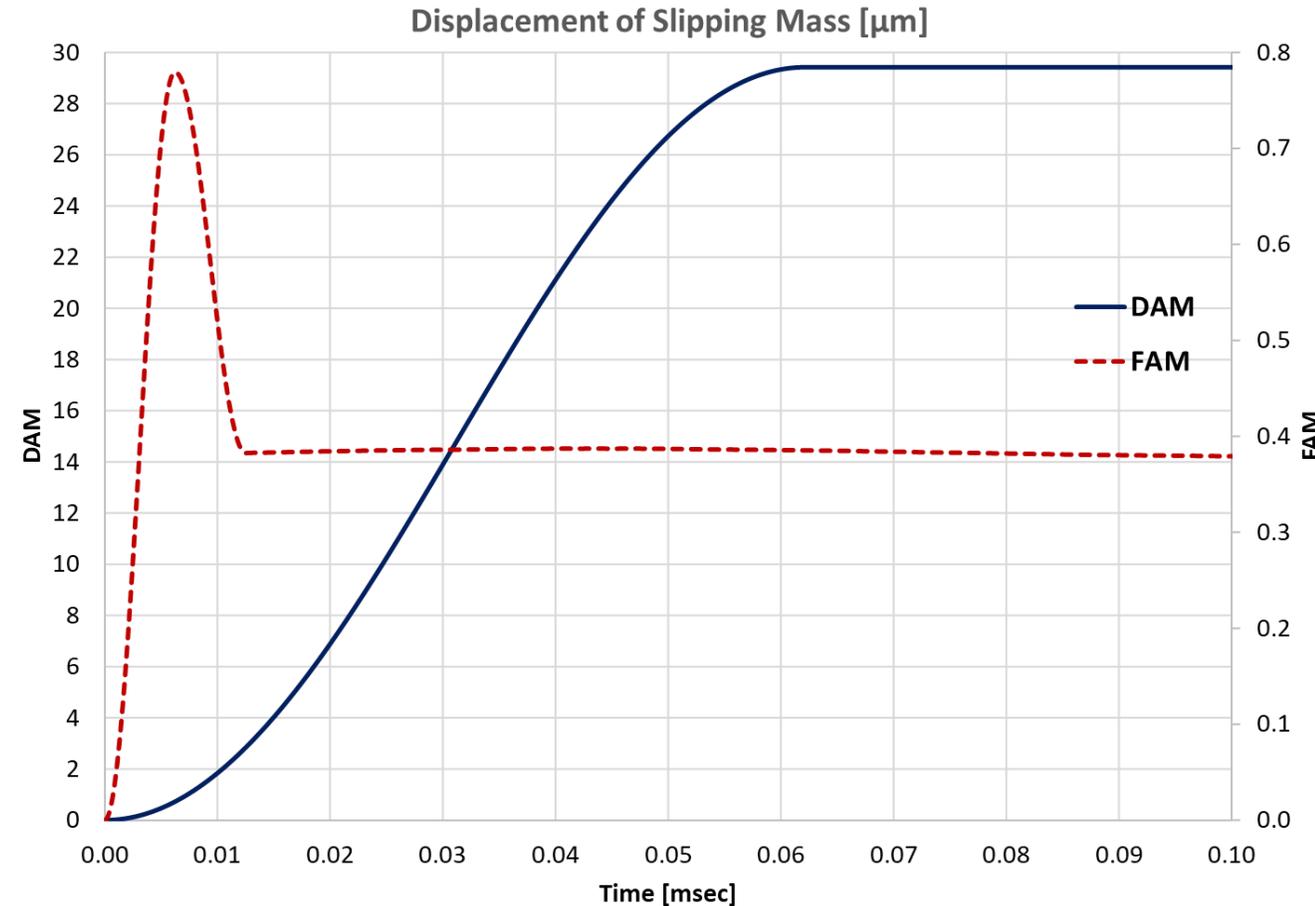
## Results: Displacement Response at 5 N Mechanical Friction Force

- For FAM the possible maximum displacement due to mechanical deformation of the mechanism is  $0.25 \mu\text{m}$
- Against a 5 N mechanical friction force, the slipping mass of the FAM achieved  $0.4 \mu\text{m}$  displacement at steady state
- Interestingly, the displacement was even larger ( $0.78 \mu\text{m}$ ) before the steady state



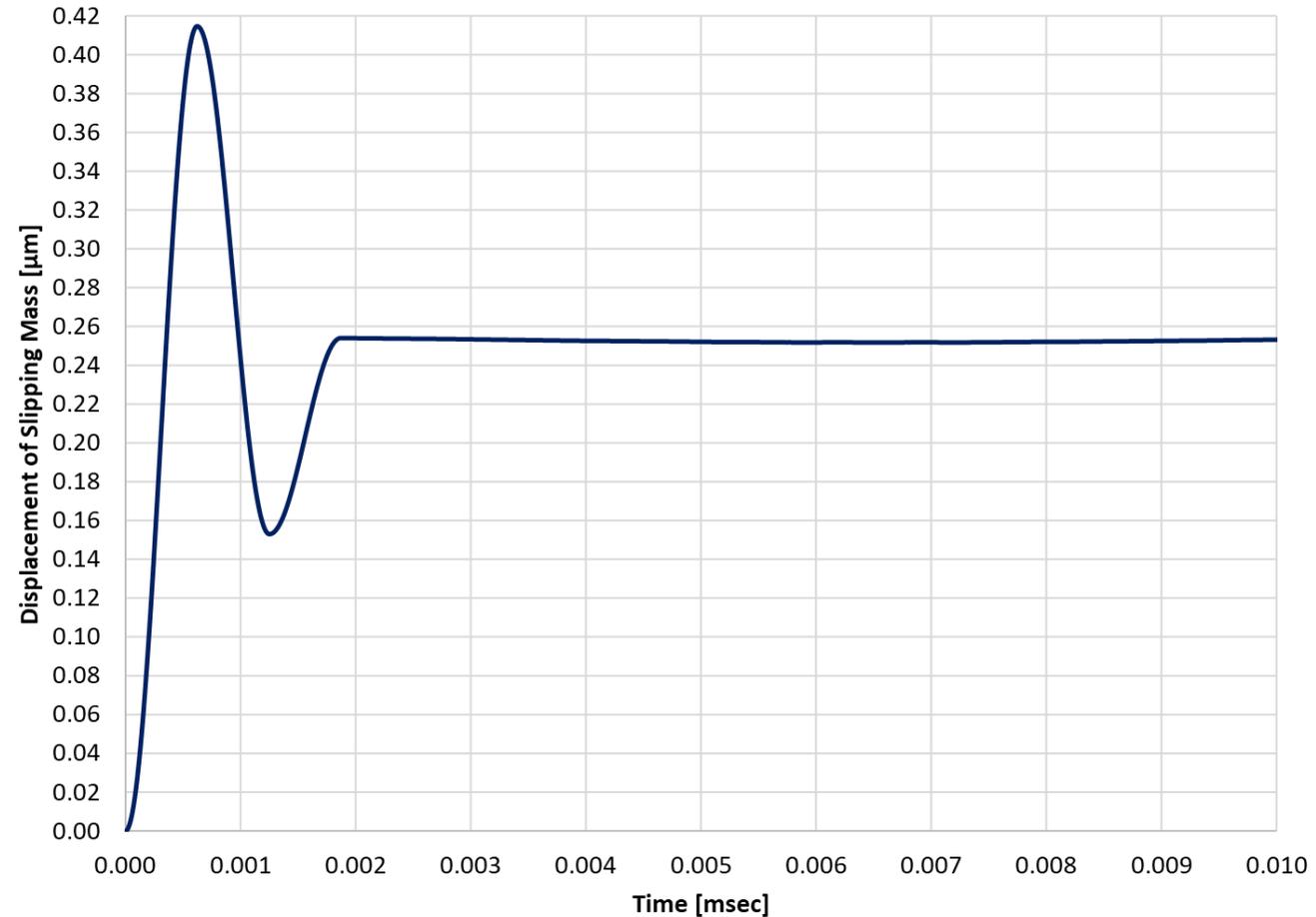
## Results: Displacement Response at 5 N Mechanical Friction Force

- Comparing the total displacement to the displacement due to mechanical deformation of the mechanism, then
  - DAM:  $29.4/25 = 1.176$
  - FAM:  $0.4/0.25 = 1.6$ ,  
 $0.78/0.25 = 3.12$  (Overshooting)
- Effect of mass acceleration on the total displacement is larger in case of FAM compared to DAM



## Results: Displacement Response at 200 N Mechanical Friction Force

- At 200 N mechanical friction force the DAM design could not work against such value
- The FAM design exhibited again overshooting behavior before it goes in steady state
- FAM:  $0.25/0.25 = 1.0$ ,  
 $0.41/0.25 = 1.64$  (Overshooting)



## Conclusion

- Miniaturized and large force actuation are design challenges in the development of piezoelectric stick-slip motors
- Displacement amplification mode mechanism improves the stroke response of a piezoelectric actuator but on the expenses of the large force actuation feature
- Alternatively, the force amplification mode mechanism improves the large force actuation feature
- Due to larger mass acceleration in force amplification mode compared with displacement amplification mode mechanism a larger mass translation was observed
- The force amplification mode exhibited overshooting behavior that would be interesting for future improvement of total stroke actuation

## References

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