

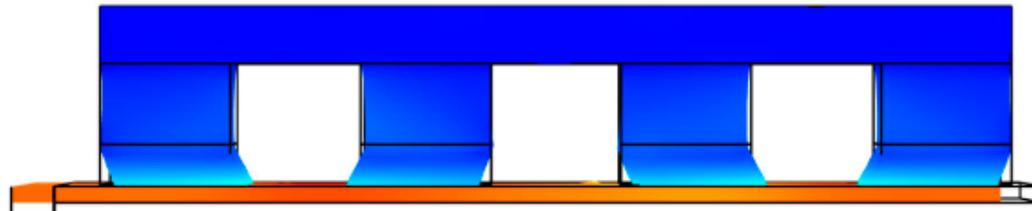
Initially Clamped Piezoelectric Inchworm Linear Motor based on Force Amplification Mechanisms Design for Miniaturized and Large Force Actuation Applications

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Introduction: Piezoelectric Inchworm Motor

- Piezoelectric inchworm motors are commonly used in precision positioning applications
- Piezoelectric inchworm motor is a multiple cooperative piezoelectric actuators either directly or indirectly contact the actuated object
- In the direct design the piezoelectric actuators are normally operate in the shear mode



Piezoelectric inchworm motor, shear mode, type P-123.01, dimensions in mm 5 x 5 x 7.5, maximum shear load 40 N and the stroke resolution is 1.6 μm [B. Zhao, 2020]

Introduction: Piezoelectric Inchworm Motor

- In the indirect design the piezoelectric actuators are integrated within mechanical mechanism which also provides protection against mechanical damage
- The stroke of inchworm motor is limited mainly by the piezoelectric actuator deformation response
- The integration of piezoelectric actuator within a mechanism can improve both displacement and force actuation capability when such mechanism is designed according to the mechanical advantage concept
- Applying of force amplification mode mechanism in piezoelectric inchworm design should therefore result in improvement of the large displacement and large force actuation capabilities

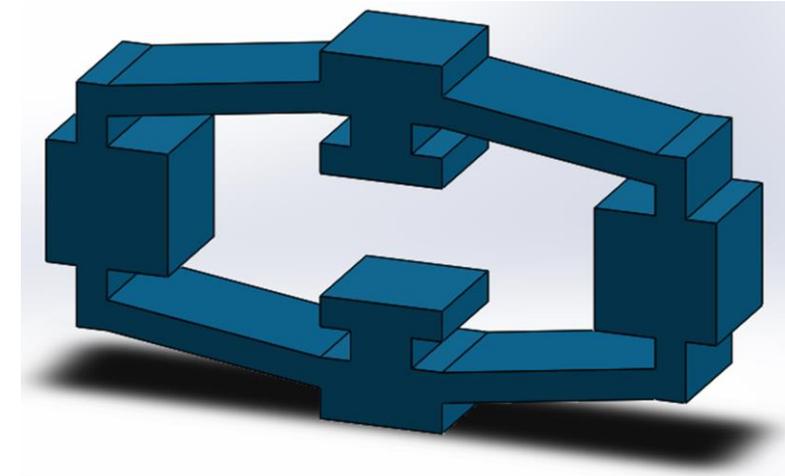
Objectives

- To develop a mechanical model based on Simulink software for a general purpose force amplification mode mechanism used in piezoelectric inchworm motor application
- To investigate by means of simulation the force and displacement actuation responses of piezoelectric inchworm motor based on amplified force mechanism

Methods: Structural Design of Force Amplification Mechanism

- Folded shape mechanical advantage mechanism
- Short axis is for the input effort force and displacement (F_E , S_E)
- Long axis is for the output force and displacement (F_L , S_L) acting on a load
- The mechanical expansion in the short (effort) axis results in mechanical compression in the long (load) axis
- Mechanical advantage factor (β) is larger than unity for force amplification mode and is represented by:

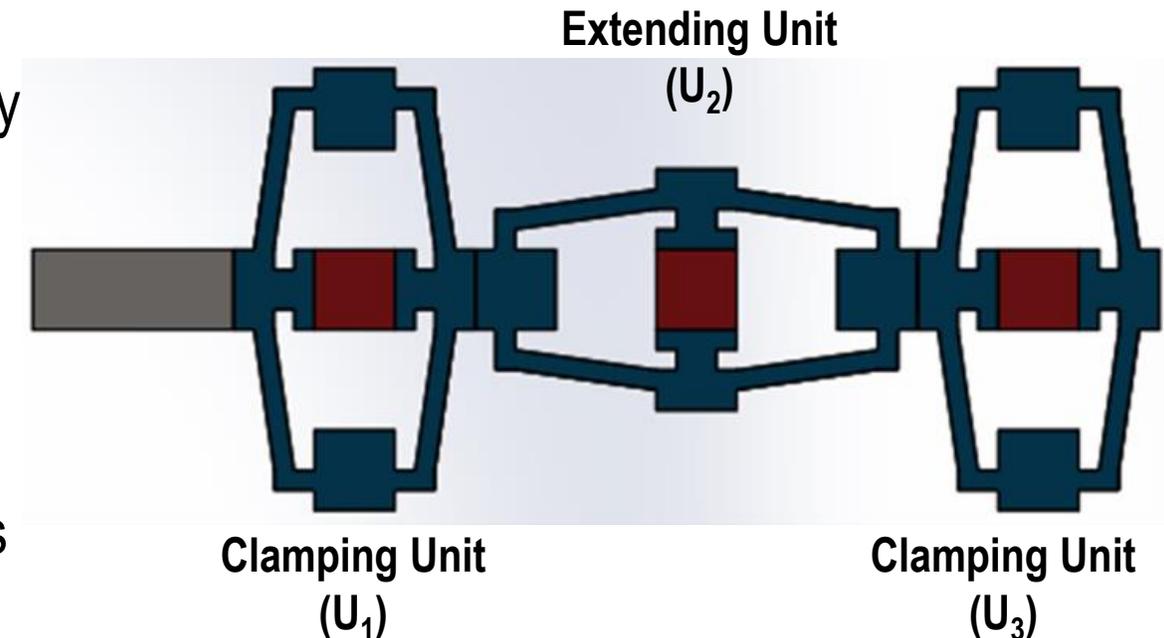
$$\beta = \frac{F_L}{F_E} = \frac{S_E}{S_L}$$



$$F_E S_E = F_L S_L$$

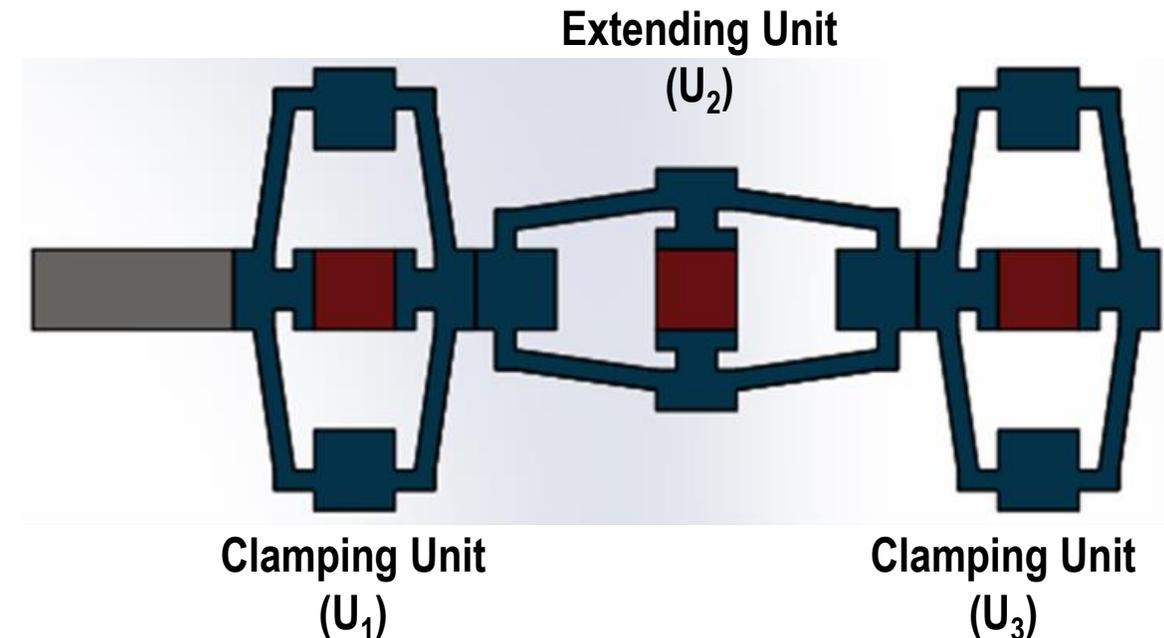
Methods: Structural Design of Amplified Force Inchworm Motor

- Three mechanisms, two for mechanical clamping and one for mechanical expansion
- Initially confined by mechanical guidance to apply self clamping feature
- The electrical activation of piezoelectric stack generates expansion deformation in the axis of piezoelectric force, while compression deformation will result at normal angle of the axis of piezoelectric force



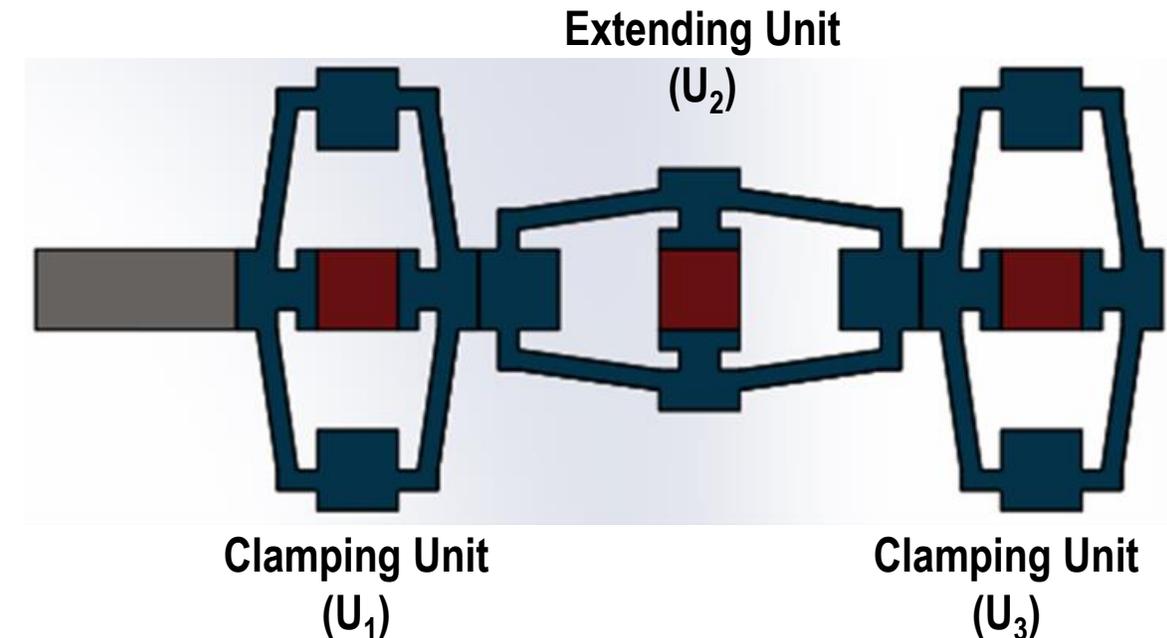
Methods: Structural Design of Amplified Force Inchworm Motor

- Electrical activation of piezoelectric stack will release the clamping unit from contact with the mechanical guidance
- On the other hand, such activation will cause the central mechanism to shrinking and thus translating the free clamping unit toward the center of the inchworm



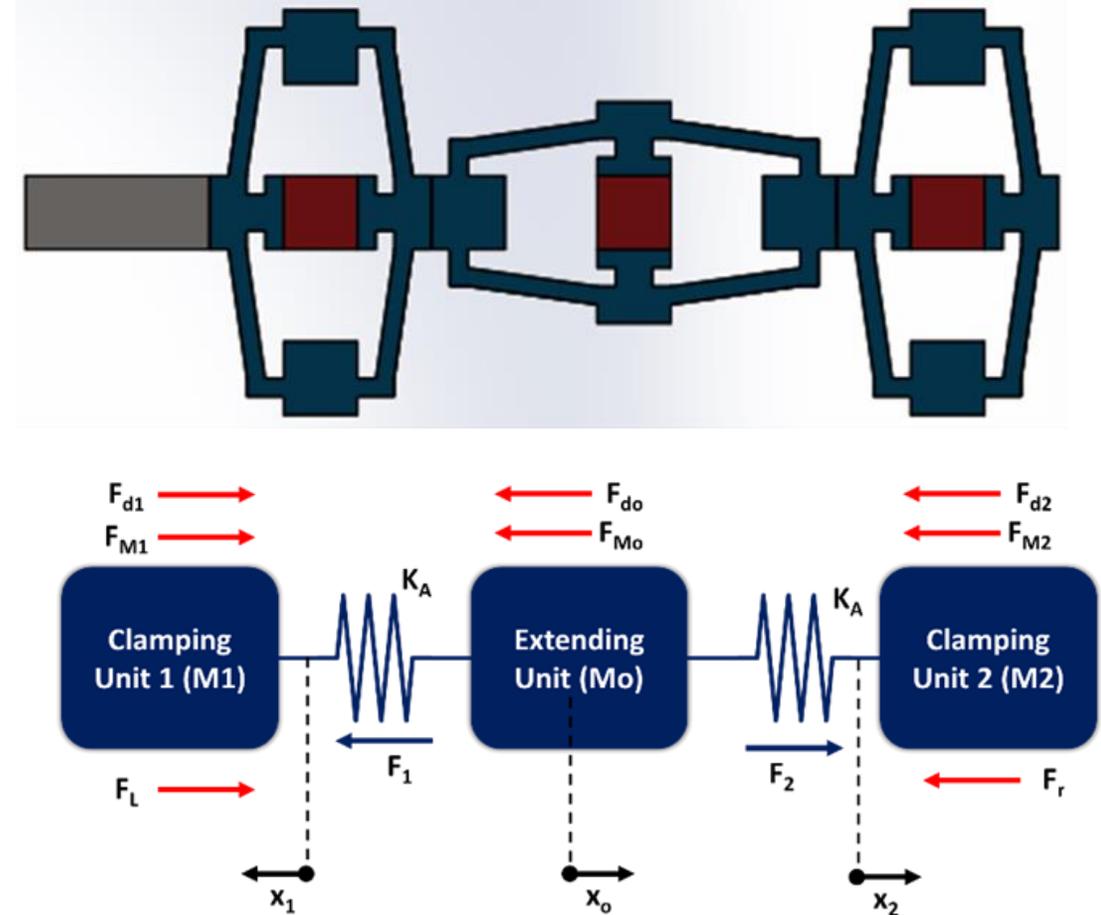
Methods: Structural Design of Amplified Force Inchworm Motor

- A stroke is performed on six steps:
 - **Step 1:** releasing mechanism U_3
 - **Step 2:** stressing mechanism U_2
 - **Step 3:** return clamping of mechanism U_3
 - **Step 4:** releasing mechanism U_1
 - **Step 5:** relaxing mechanism U_2
 - **Step 6:** return clamping of mechanism U_1



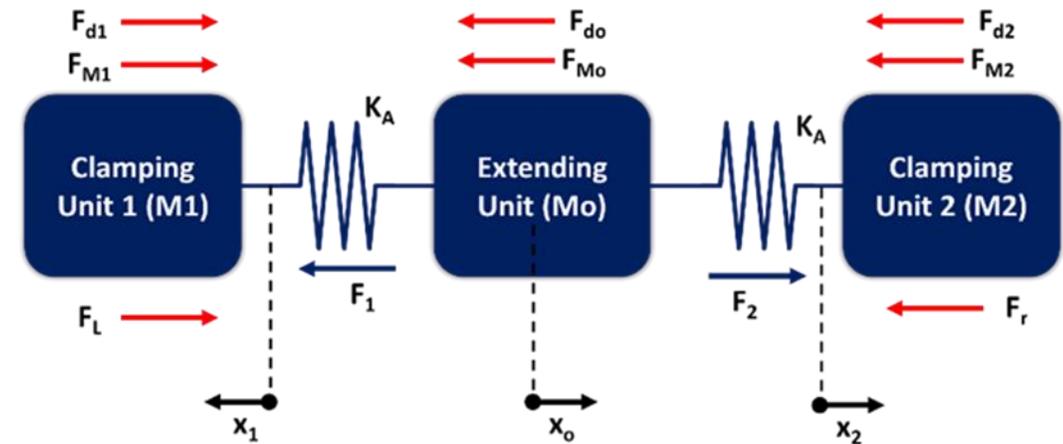
Methods: Mechanical System Modelling

- The inchworm motor can be modelled by a three coupled mass blocks
- The model represents the system when one clamping unit is released while the extending unit is stressed (the corresponding piezoelectric stacks are electrically polarized)
- Once the piezoelectric stack of the extending unit is deactivated (assuming impulse response) the stored elastic energy will be released causing mass acceleration



Methods: Mathematical Modelling

- The three coupled mass system is represented by mathematical equations
- From these equations the dynamic response of 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



$$x_o = 0.5 (x_2 - x_1)$$

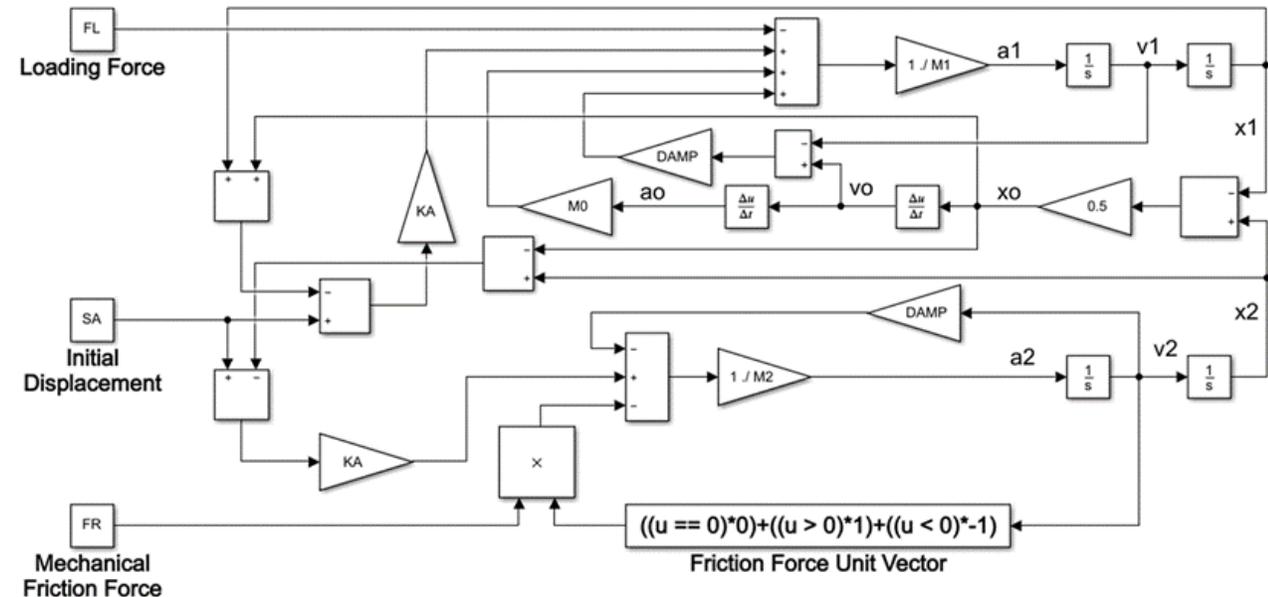
$$a_1 = \frac{1}{m_1} (K_A(S_A - (x_1 + x_o)) + m_o a_o + b(v_o - v_1) - F_L)$$

$$a_o = \frac{1}{m_o} (m_1 a_1 - m_2 a_2 + b(v_1 - v_2 - v_o) + F_L - F_r)$$

$$a_2 = \frac{1}{m_2} (K_A(S_A - (x_2 - x_o)) - b v_2 - F_r)$$

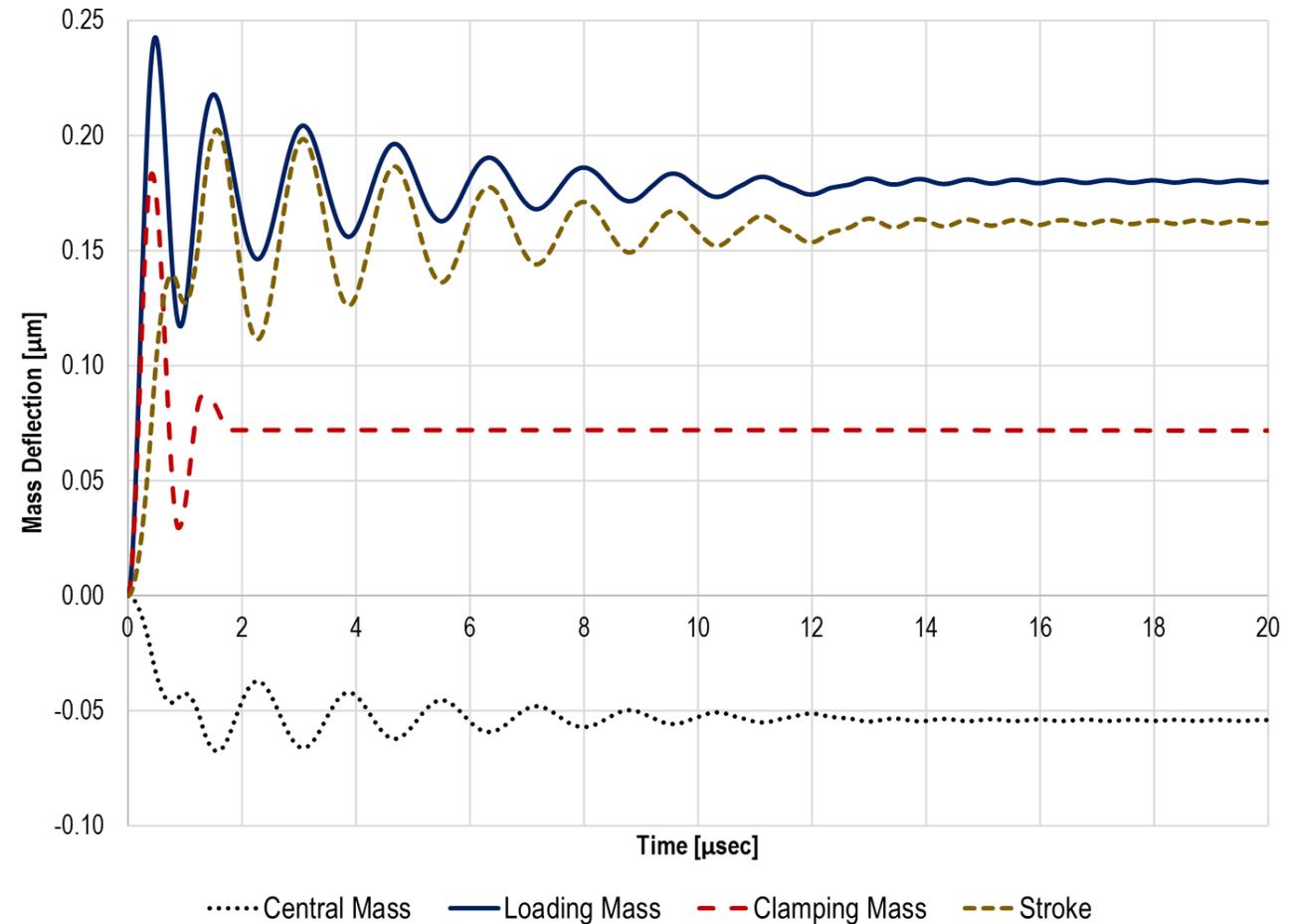
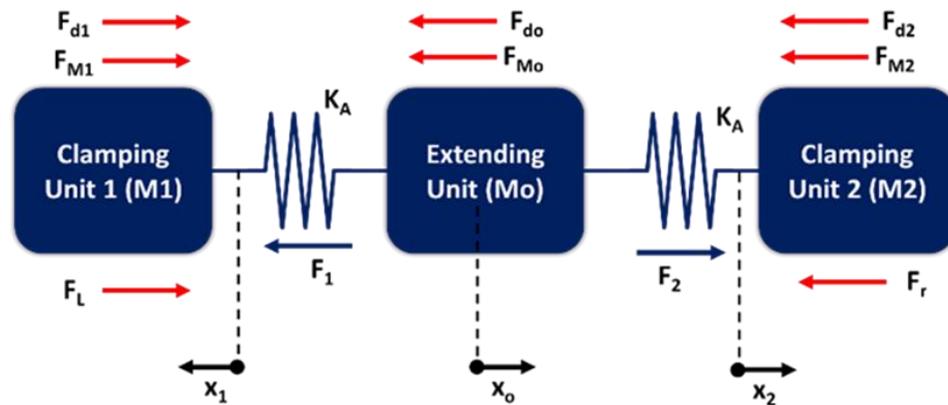
Methods: Simulink Modelling

- In this model, each mass component is 0.2 g
- A piezoelectric stack was arbitrarily considered such that a stroke of 1.25 μm is generated at 125 N applied force
- For the FAM configuration, the design parameters were calculated such that the stiffness constant of mechanism is 10 GN/n and initially prestressed by 0.125 μm from each side, therefore the expected resultant stroke is 0.25 μm



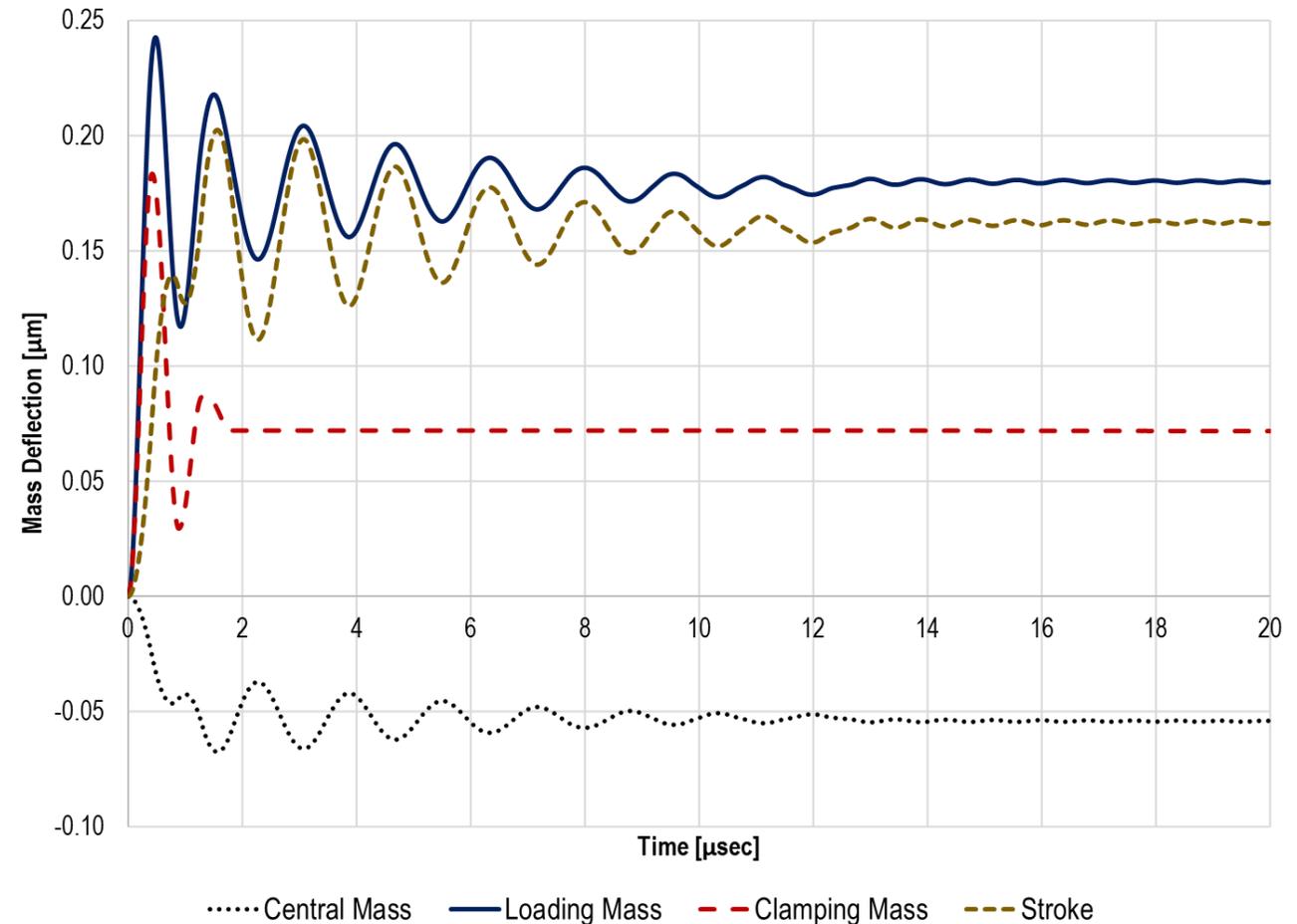
Results: Deflection Response of Mass Components at 200 N Mechanical Friction

- The deflection response of each mass component was extracted and the resultant total stroke was accordingly calculated



Results: Deflection Response of Mass Components at 200 N Mechanical Friction

- The expected total stroke is $0.25\ \mu\text{m}$
- The actual total stroke at steady state is $0.16\ \mu\text{m}$
- A backlash of $0.09\ \mu\text{m}$ resulted due to the mechanical oscillation of the clamping mass (M2)
- Interestingly, a larger stroke value of $0.2\ \mu\text{m}$ is available at the second peak of the oscillation behavior



Conclusion

- Miniaturized and large force actuation are design challenges in the development of piezoelectric inchworm motors
- A monolithic design based on force amplification mechanism concept was proposed for the development of miniaturized and large force actuation of piezoelectric inchworm motor
- The dynamic response of the proposed design of inchworm motor was extracted by means of Simulink model where the simulation results showed that the clamping mass was subjected to mechanical oscillation and caused a backlash
- The effect of applying different mass amounts should be investigated as an approach to reduce the backlash effect

References

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