Effect of Mechanical Loading and Increased Gap on the Dynamic Response of Multiple Degree of Freedom Electrostatic Actuator

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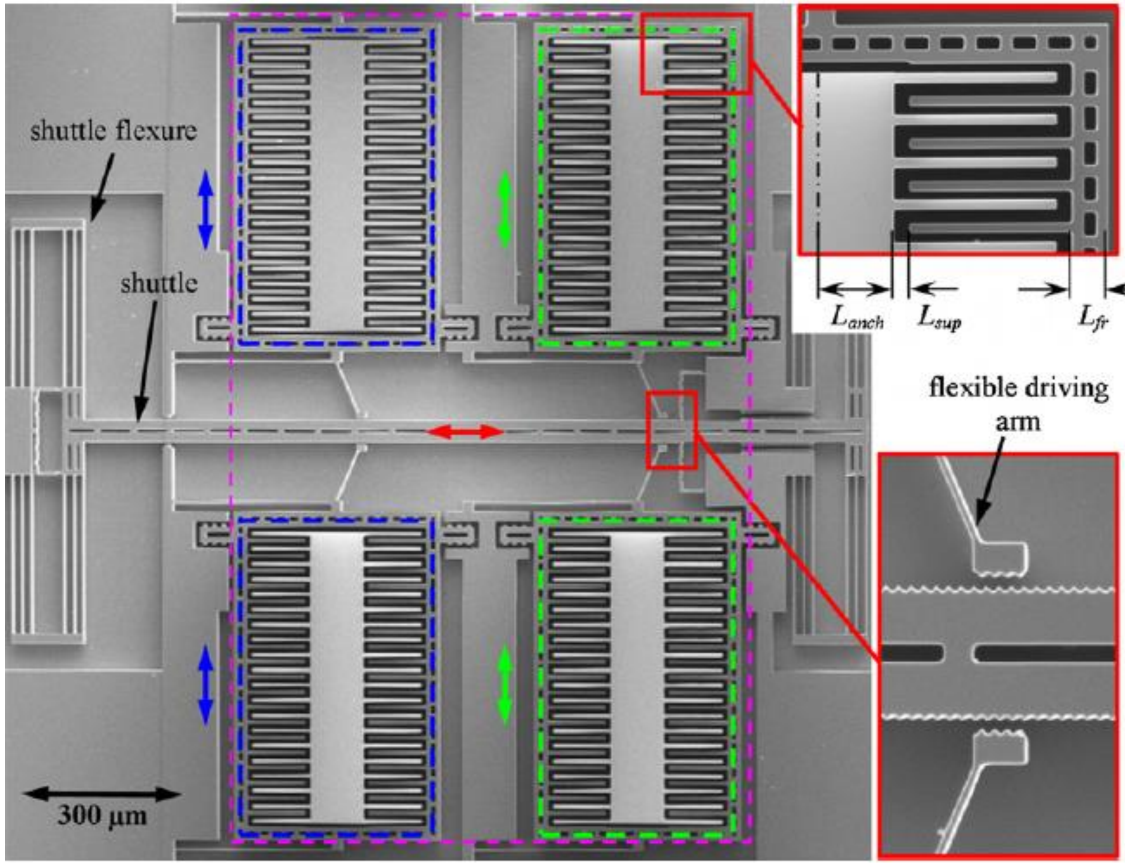
Introduction: Electrostatic Inchworm Motor

- Electrostatic actuator based on silicon technology is a potential approach for realizing a miniaturized inchworm motor
- Normally a gap closing electrostatic actuator is applied due to the larger generated electrostatic force compared to the area overlapping design
- Force actuation level in electrostatic inchworm motor is still very low (few mN)
- Also the pull-in phenomena causes stability and controllability problems



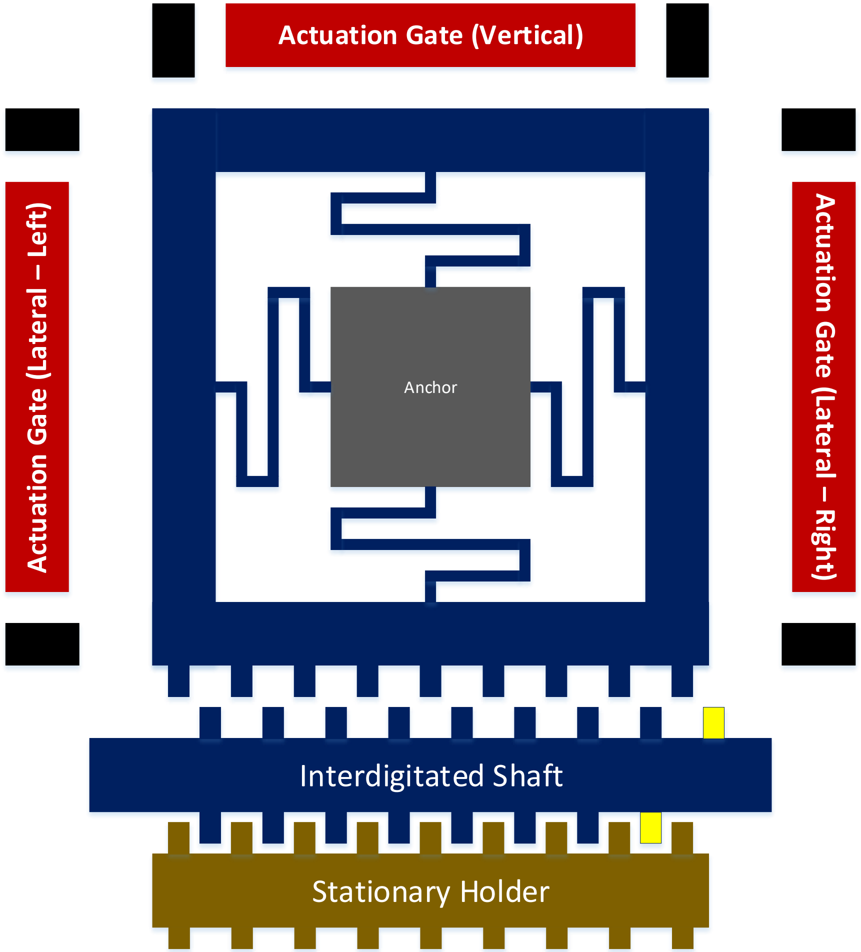
Electrostatic inchworm fabricated based on silicon-on-insulator (SOI) technology, consists of shuttles and flexible arms, perform a 10 µm stroke against 1.88 mN at 110 V. Snapping failure occurred at load of 3.7 mN **[I. Penskiy, 2013]**

Objectives

- To develop an electromechanical model based on Simulink software for a multiple degree of freedom electrostatic actuator used in inchworm motor application
- To investigate by means of simulation the effect of mechanical loading variation on the response of the proposed multiple degree of freedom electrostatic actuator
- To investigate by means of simulation the effect of increased gap on the response of the proposed multiple degree of freedom electrostatic actuator
- To extract potential design approaches for improving the actuator response

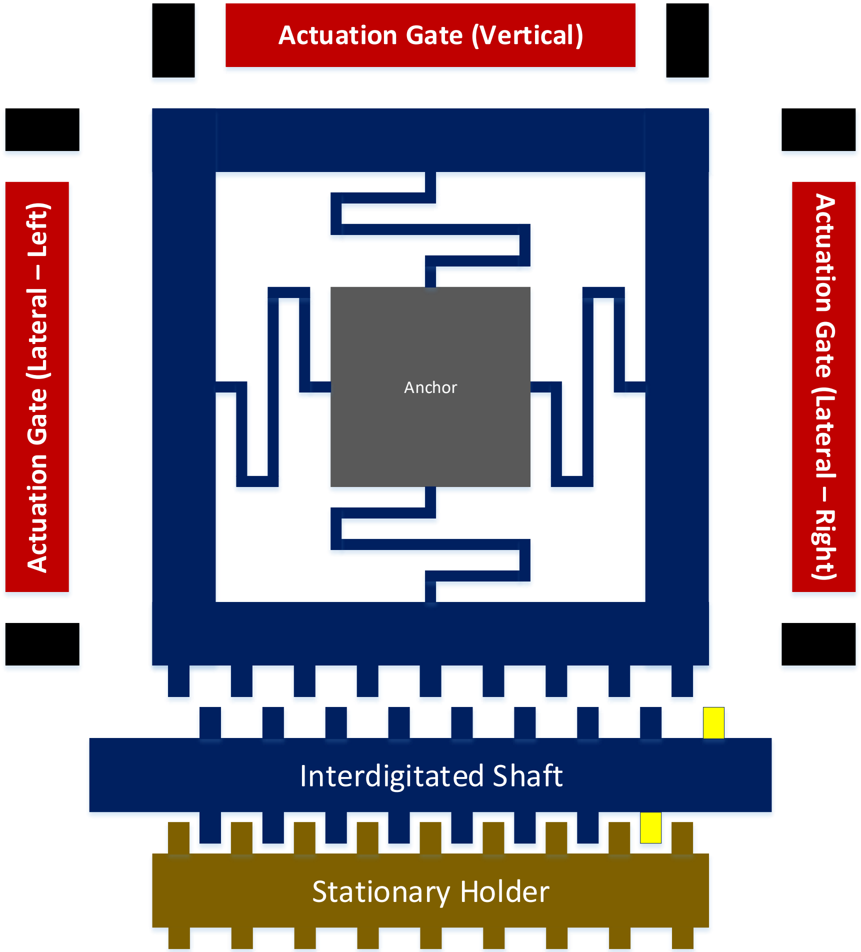
Methods: Structural Design of Multiple DOF Electrostatic Actuator

- A suspended frame movable in the in-plane directions
- Surrounding mechanical stoppers and fixed electrodes for electrical actuation
- Comb structures for clutching and motion translation
- Interdigitated shaft movable in the in-plane directions
- Gap closing capacitors actuated through the surrounding fixed electrodes (actuation gates)



Methods: Operation of Multiple DOF Electrostatic Actuator

- Initially the suspended frame is mechanically detached from the interdigitated shaft and electrically at neutral potential voltage
- Extra actuation electrodes (not presented) are used to move the interdigitated shaft upward to release it from the stationary holder and simultaneously to clutch the comb structures with the suspended frame
- When the right actuation gate is electrically connected to a specific voltage then electrostatic force is generated and pulls the suspended frame as well as the interdigitated shaft toward the right side



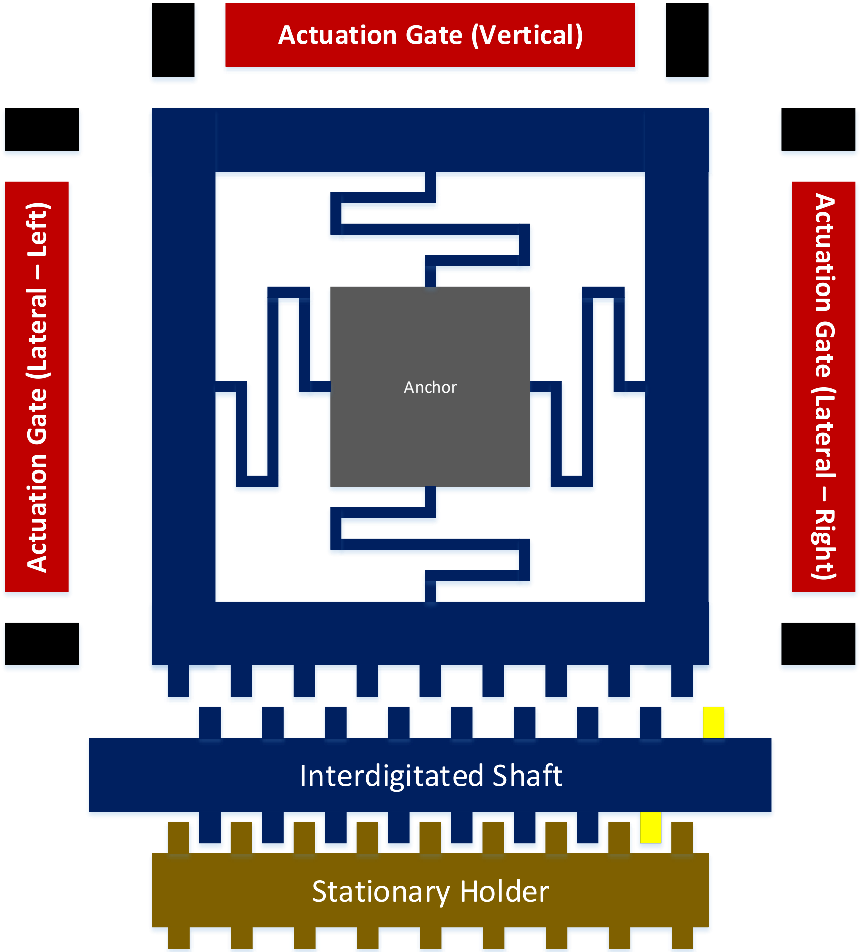
Methods: Operation of Multiple DOF Electrostatic Actuator

- When the right actuation gate is electrically connected to a specific voltage then electrostatic force is generated and pulls the suspended frame as well as the interdigitated shaft toward the right hand side

- The extra actuation electrodes are then deactivated electrically so that the interdigitated shaft is pulled downward back to the clutching with stationary holder

- The right actuation gate is electrically deactivated so that the suspended frame return back to the original position

- The process is repeated to perform further strokes

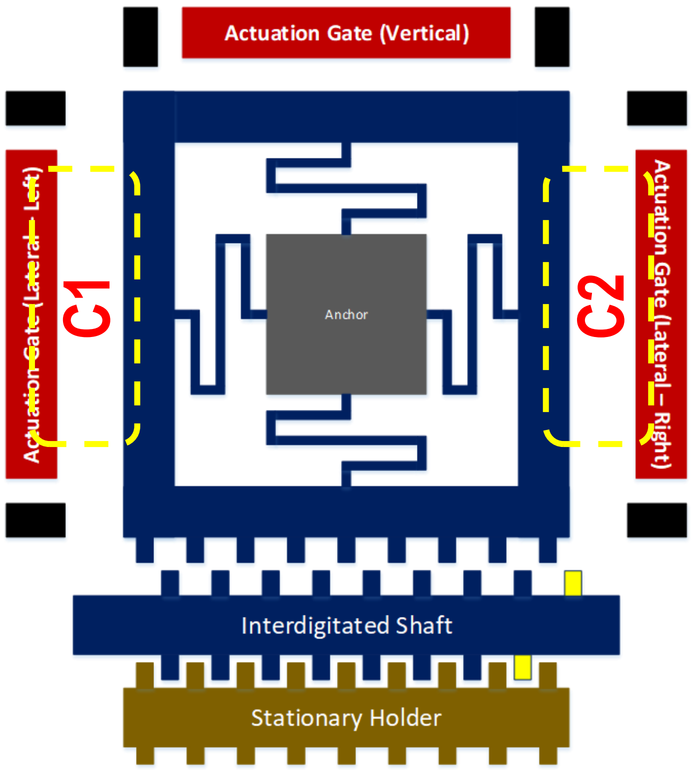


Methods: Mathematical Modelling

- The suspended mass is a mechanical oscillator and represented by mass-spring-damper (m-k-b) model
- Mechanical oscillator is coupled electrically by variable capacitors (C_1, C_2) through which electrostatic force influence the dynamic response of the suspended frame
- Mechanical stoppers represent a kind of mechanical springs with specific stiffness constants (k_s) and start influencing the dynamic behavior of the suspended frame at the instant of collision

$$C_1 = \frac{\varepsilon_o \, \varepsilon_r \, L \, H}{G_{C1} + x}$$

$$C_2 = \frac{\varepsilon_o \, \varepsilon_r \, L \, H}{G_{C2} - x}$$

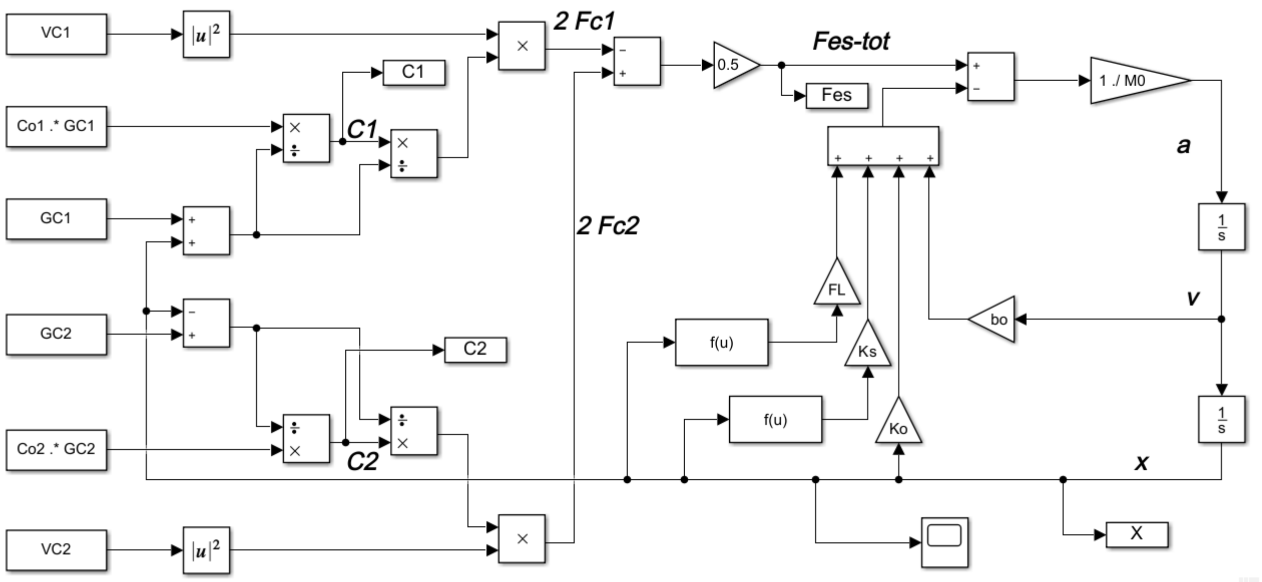


$$F_{int} = m\,a + b\,v + k\,x + k_s\,x_{s1} + k_s\,x_{s2}$$

$$F_{ext} = 0.5\left(\frac{V_{C2}^2\,C_2}{G_{C2} - x} - \frac{V_{C1}^2\,C_1}{G_{C1} + x}\right) - F_L$$

Methods: Simulink Modelling

- In this model, arbitrary dimensions were elected such that the actuation gate has:
  - 250 µm length, 50 µm height, 4.5µm initial gap with suspended frame
- Also, in the model the following parameters values were applied
  - total mass of 4 µg, viscosity damping factor 0.1 N.s/m, stiffness constant 34kN/m for mechanical suspension and 34000 GN/m for mechanical stoppers



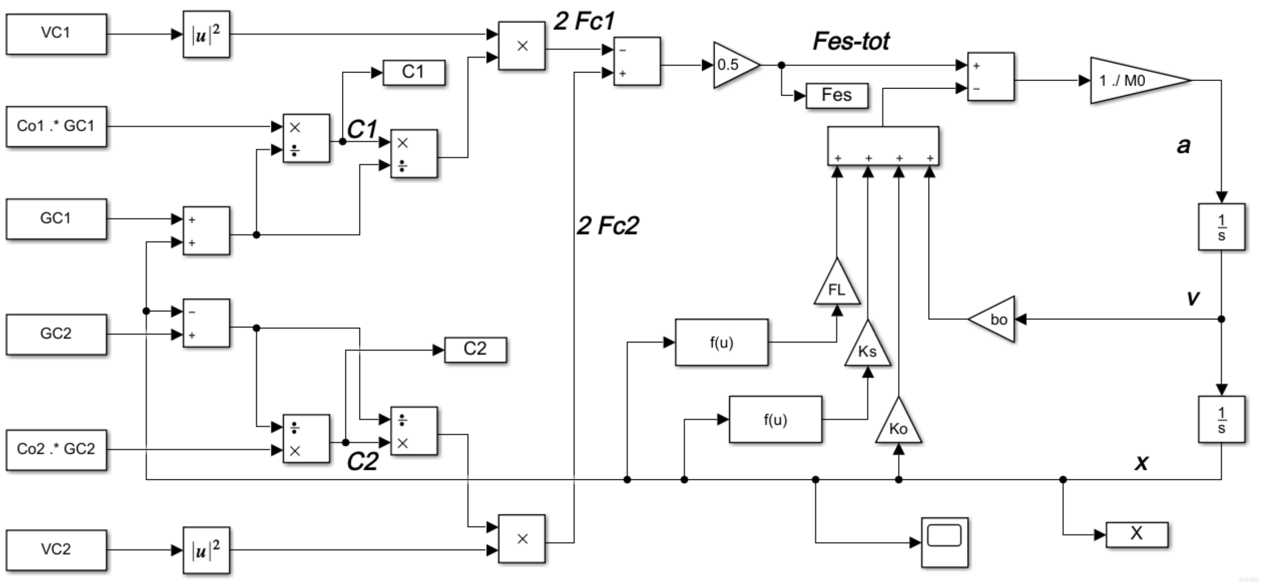
$$F_{int} = m\,a + b\,v + k\,x + k_s\,x_{s1} + k_s\,x_{s2}$$

$$F_{ext} = 0.5\left(\frac{V_{C2}^2\,C_2}{G_{C2} - x} - \frac{V_{C1}^2\,C_1}{G_{C1} + x}\right) - F_L$$

$$C_1 = \frac{\varepsilon_o\,\varepsilon_r\,L\,H}{G_{C1} + x} \qquad C_2 = \frac{\varepsilon_o\,\varepsilon_r\,L\,H}{G_{C2} - x}$$

Methods: Simulink Modelling

- According to the selected design parameters values the pull-in voltage is 2.88 kV
- For the electrostatic actuation a step signal of 10 kV was applied
- A mechanical load was assumed at 2 µm apart from the suspended frame at rest state



$$F_{int} = m\,a + b\,v + k\,x + k_s\,x_{s1} + k_s\,x_{s2}$$

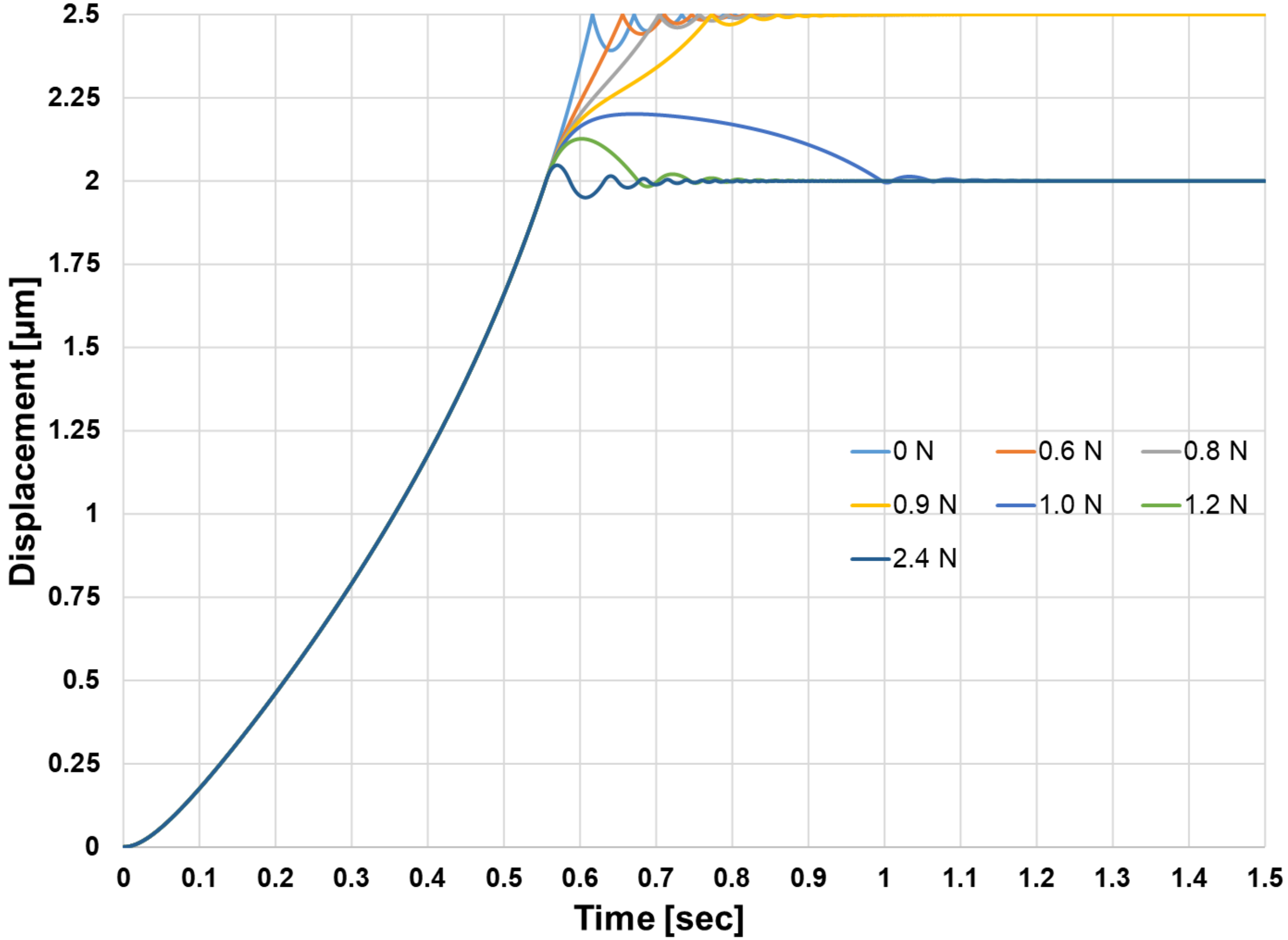
$$F_{ext} = 0.5\left(\frac{V_{C2}^2\,C_2}{G_{C2} - x} - \frac{V_{C1}^2\,C_1}{G_{C1} + x}\right) - F_L$$

$$C_1 = \frac{\varepsilon_o\,\varepsilon_r\,L\,H}{G_{C1} + x}$$

$$C_2 = \frac{\varepsilon_o\,\varepsilon_r\,L\,H}{G_{C2} - x}$$

Results: Displacement Response at different Mechanical Loads

- The mechanical load value was varied from 0 to 2.4 N
- Mechanical bouncing was observed at all cases such that the larger the mechanical load the lower mechanical bouncing peak
- The maximum bouncing peak is 112.5 nm at no load and 25 nm at 0.9 N
- This bouncing response will cause actuation stability problem if the comb structure is included in the model

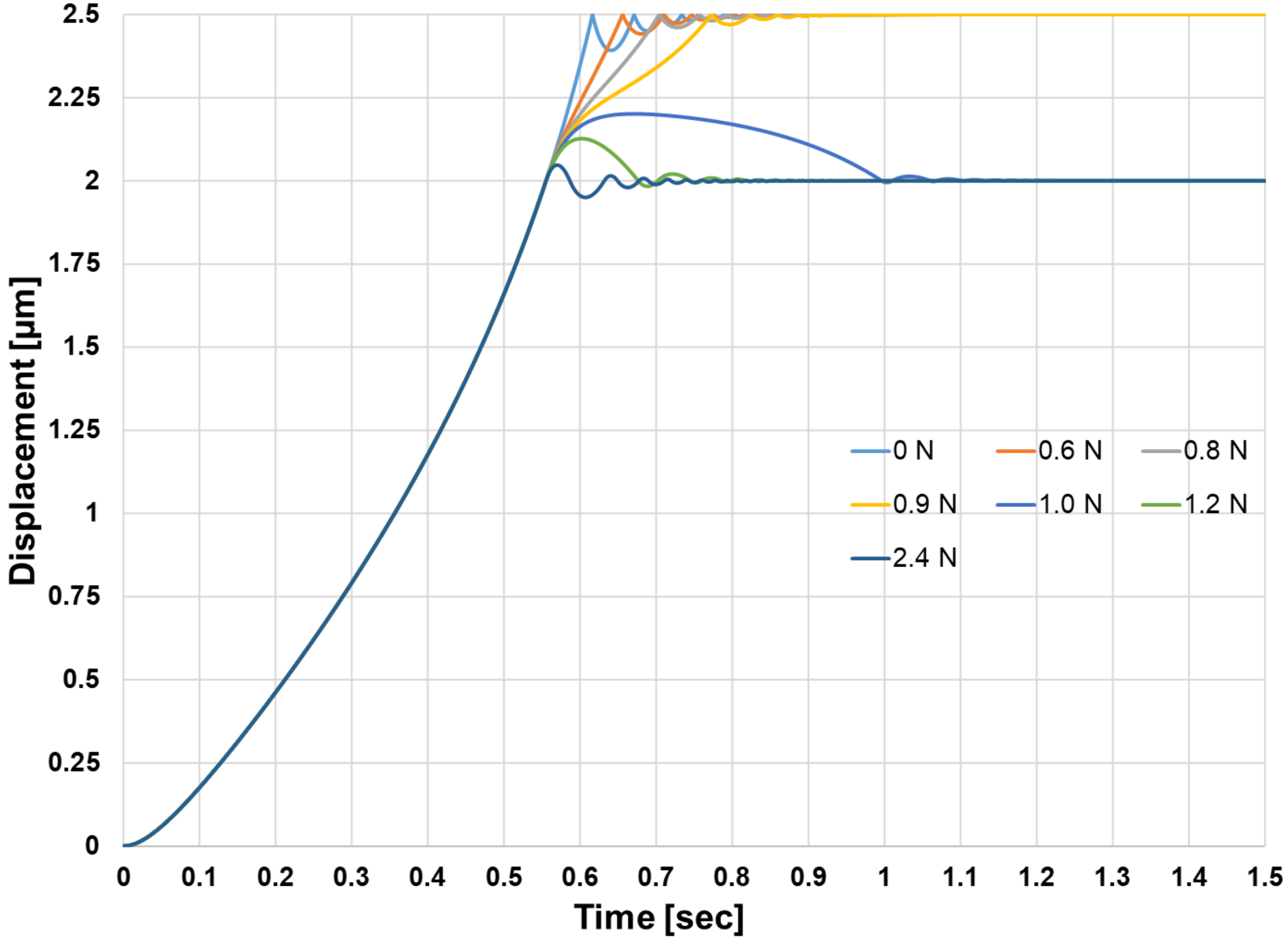


Results: Displacement Response at different Mechanical Loads

- Increasing of the load caused decreasing of the slope in the displacement response

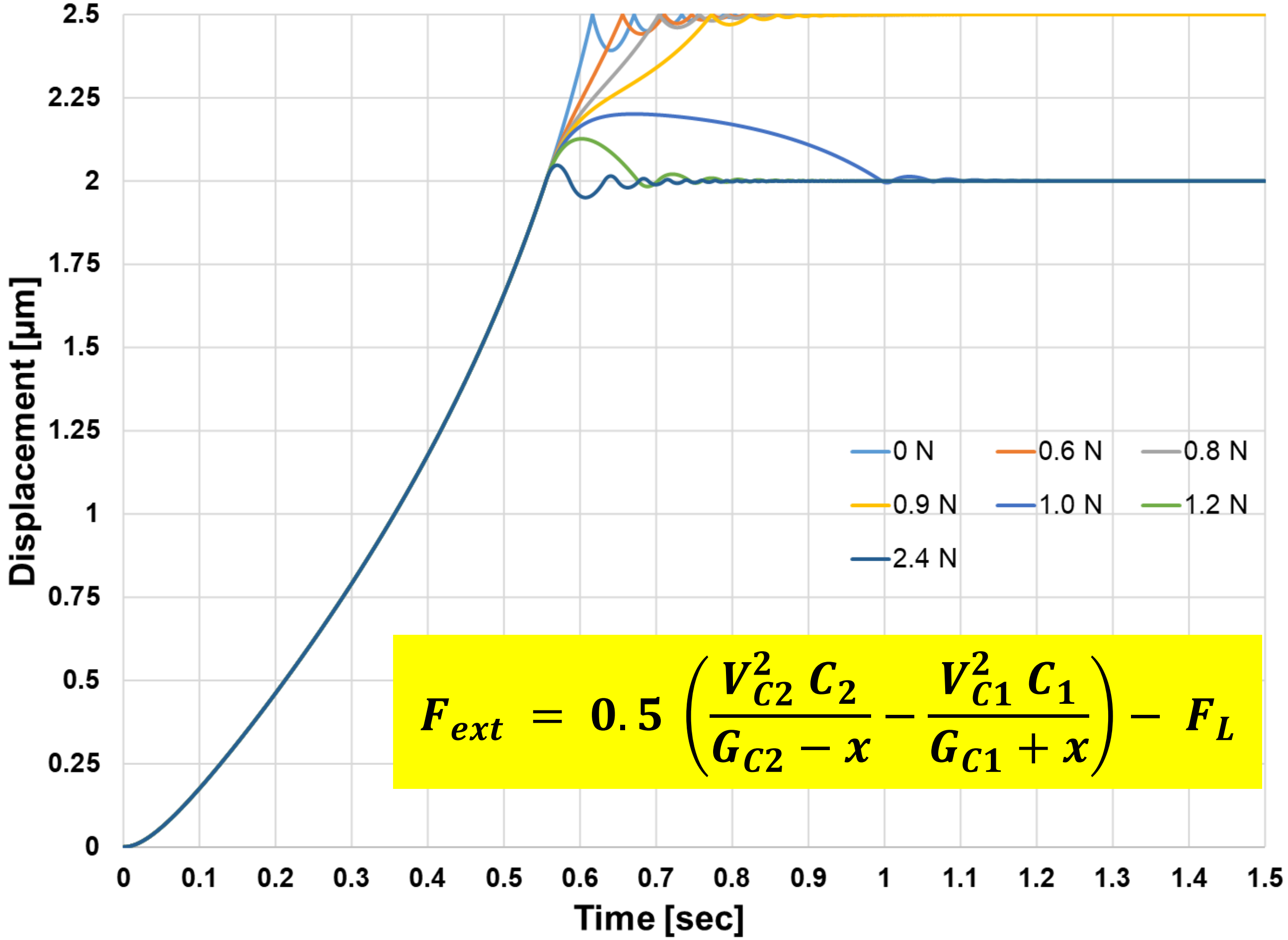
- The slope decreasing of displacement response means that velocity and acceleration were decreased and therefore less collision effect appeared as lower bouncing peak

- Applying specific control signal at the variable capacitor (C_1) will be a potential approach for applying load such that the bouncing effect is reduced



Results: Displacement Response at different Mechanical Loads

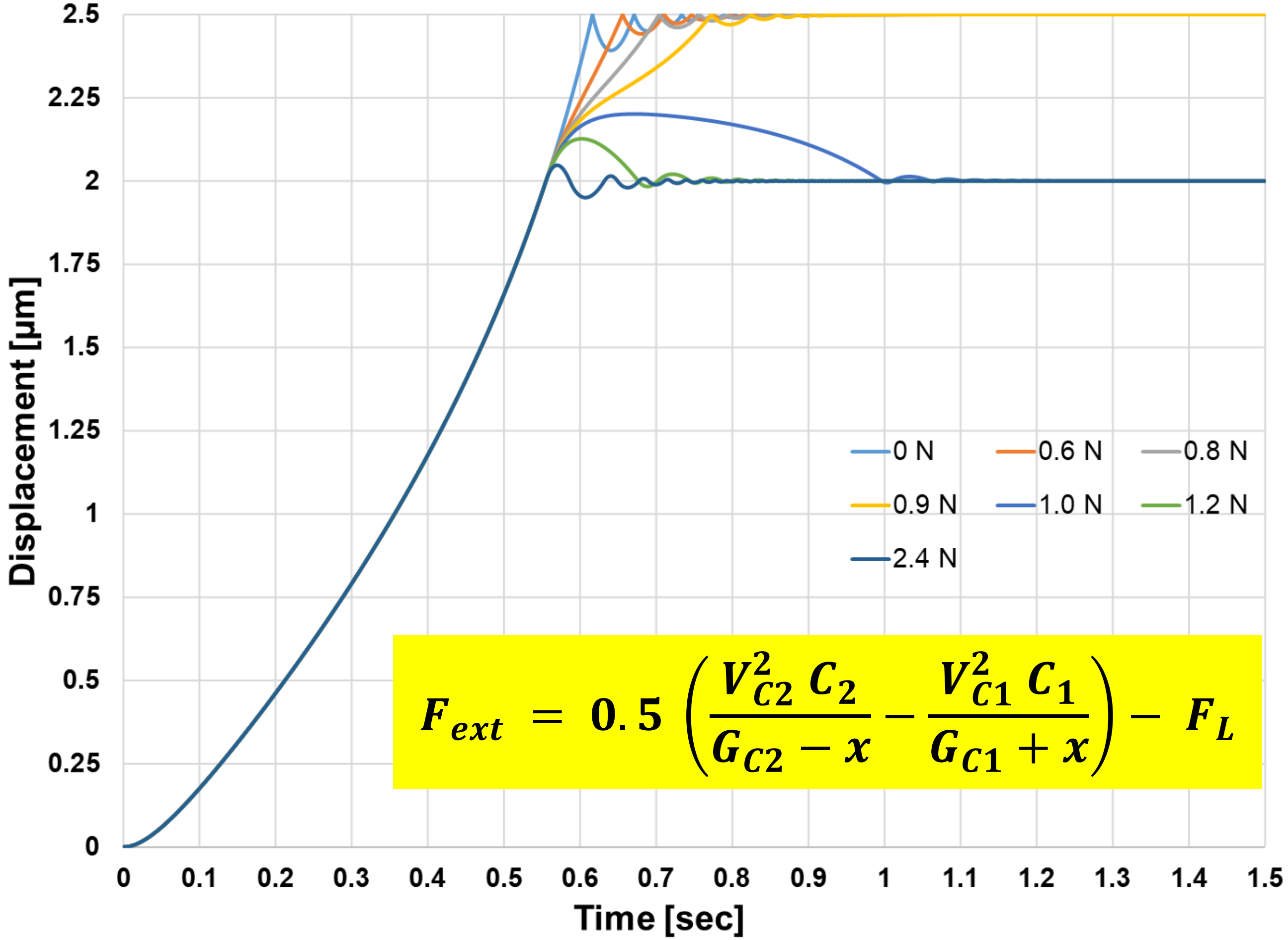
- The maximum displacement 2.5 µm was achieved between 0 and 0.9 N loading
- At 1 N load the actuator performed for a slight time further displacement before it return back after roughly 1 sec to 2 µm position at which the mechanical load was initially set
- At the instant of load impact the net excitation force (electrostatic and load) decreases abruptly and thus both acceleration and velocity decreases



$$F_{ext} = 0.5\left(\frac{V_{C2}^2\, C_2}{G_{C2} - x} - \frac{V_{C1}^2\, C_1}{G_{C1} + x}\right) - F_L$$

Results: Displacement Response at different Mechanical Loads

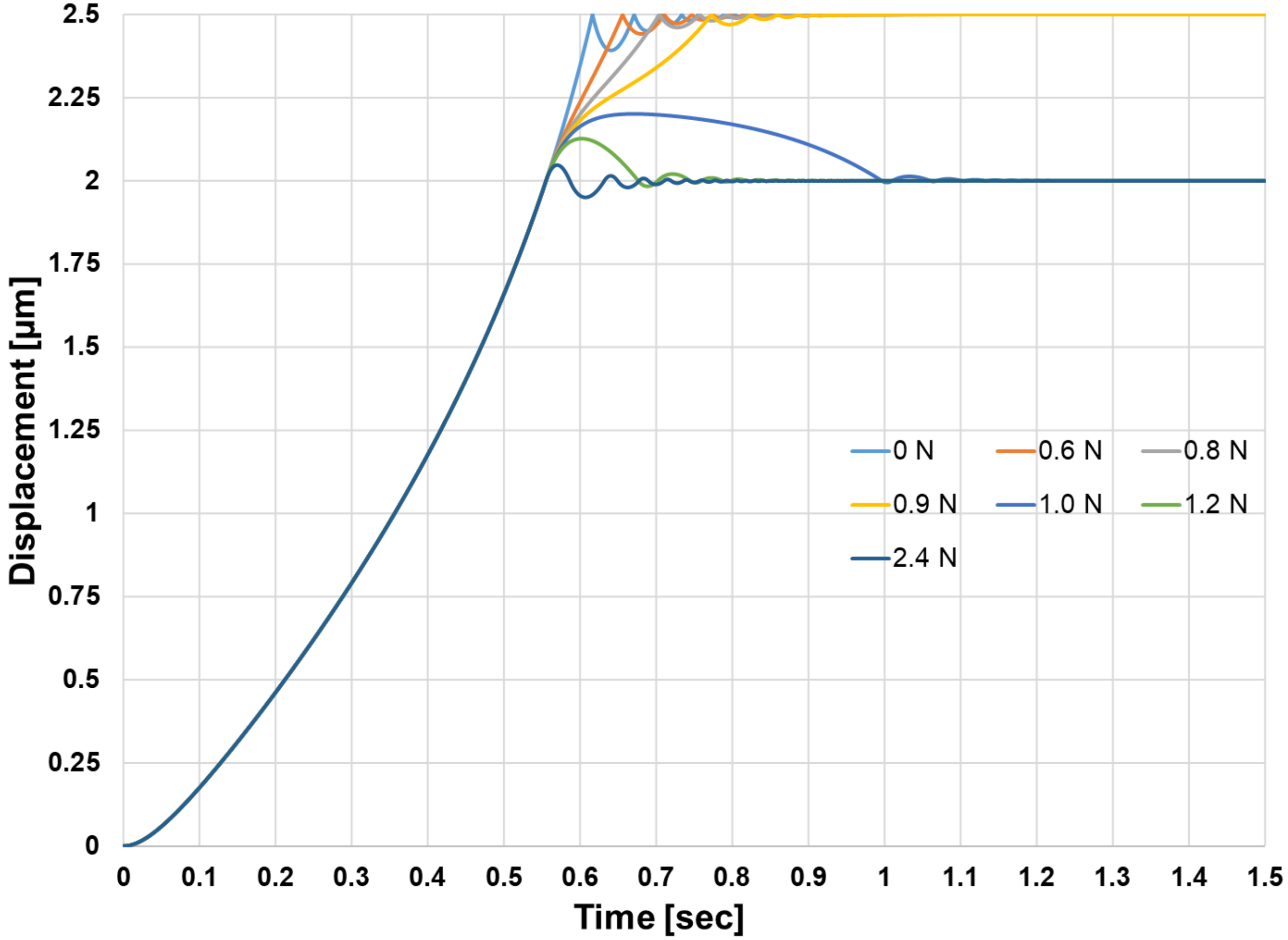
- At zero velocity the load dominates the excitation force so that the displacement starts decreasing
- As the displacement decreases the resultant electrostatic force decreases too
- The final state is at which the actuator bounces with extremely small peaks around the 2 µm position (initial proximity of load)



$$F_{ext} = 0.5\left(\frac{V_{C2}^2\,C_2}{G_{C2}-x} - \frac{V_{C1}^2\,C_1}{G_{C1}+x}\right) - F_L$$

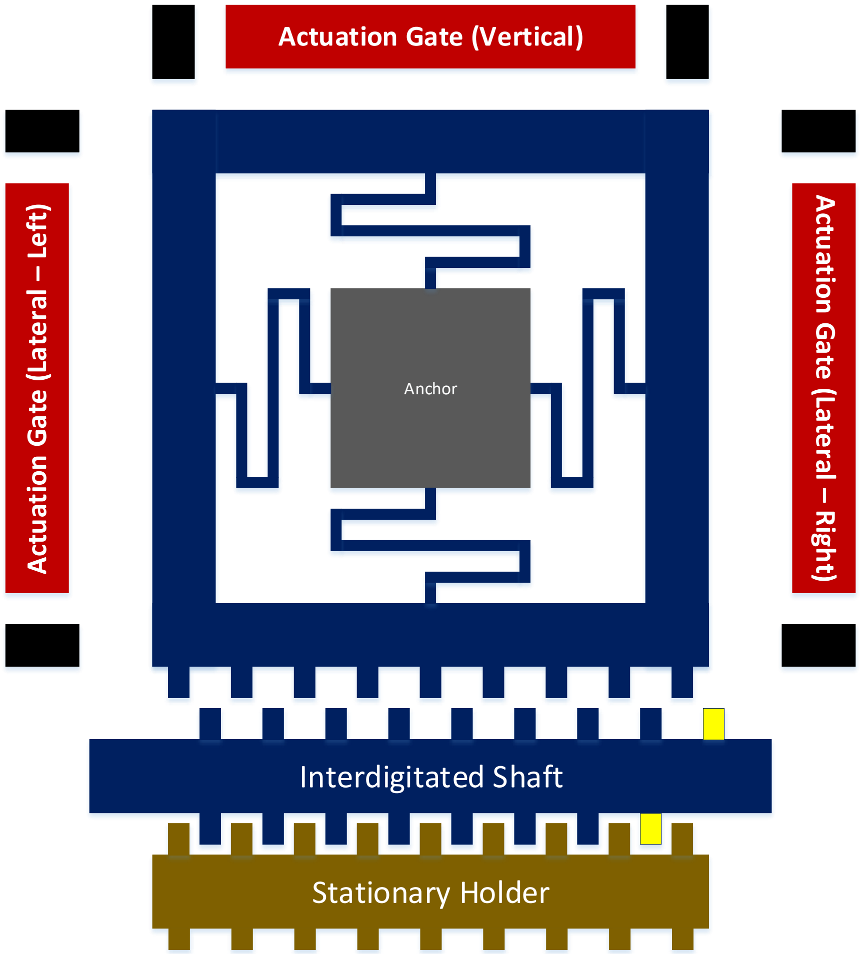
Results: Displacement Response at different Mechanical Loads

- In terms of bouncing transient time, a value of 900 msec is roughly the same for the cases between no load and 0.9 N
- For larger loading than 0.9 N the bouncing transient time is between 0.8 to 1.2 sec
- Bouncing transient time will influence the design of switching signal of the actuator
- Also bouncing peaks will influence the design of the gap between electrodes of the comb structures



Results: Displacement Response at Increased Gap

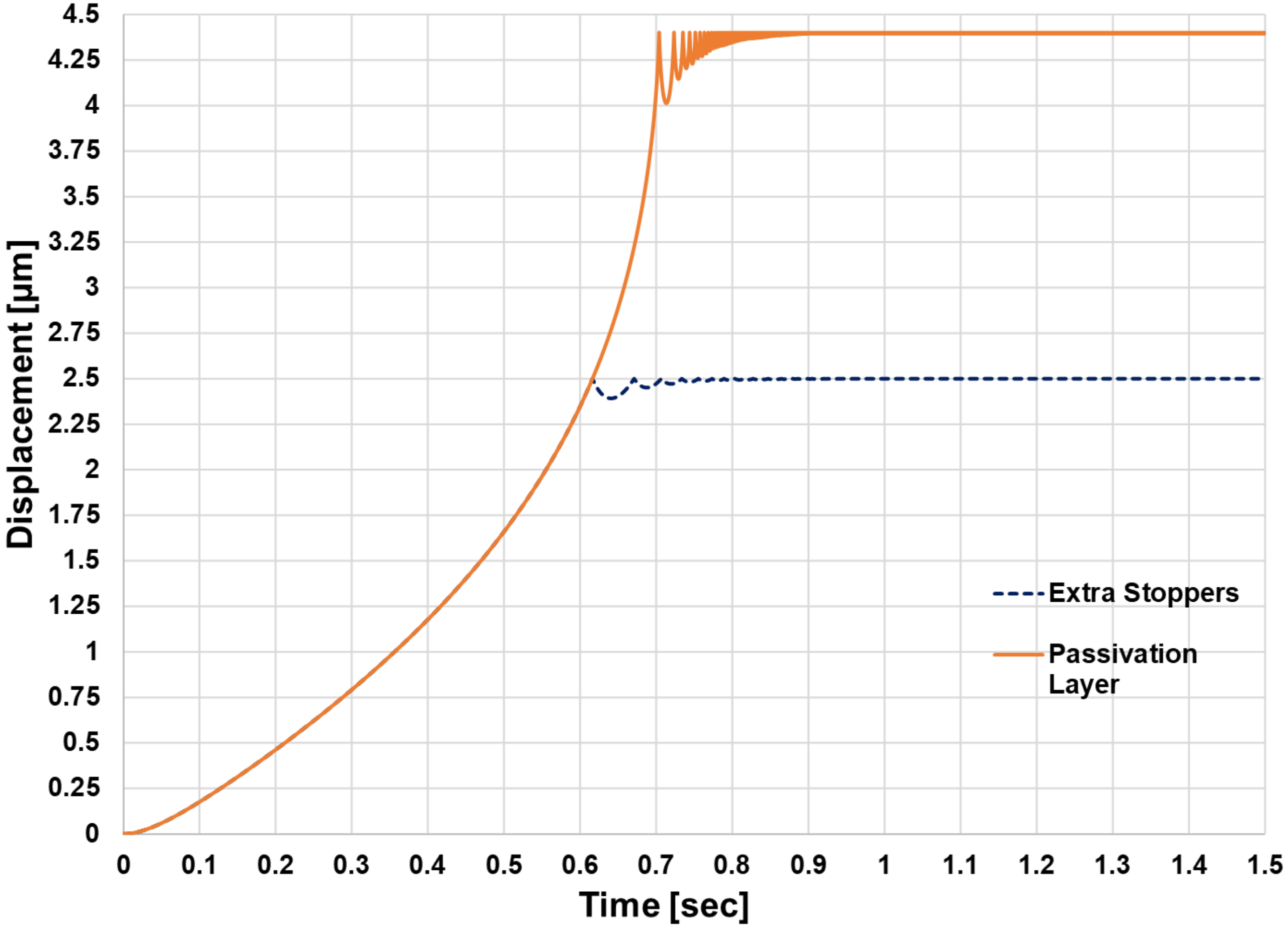
- Mechanical stoppers are necessary to prevent electrical short circuit between suspended frame and actuation gate
- Alternative solution is the passivation of the actuation gate so that mechanical stoppers can be removed
- This provides more space and larger gap utilization
- In this part, the full initial gap (4.4 μm) between suspended frame and actuation gate is used providing that the passivation layer is 100 nm
- The simulation was run at no load



Results: Displacement Response at Increased Gap

$$F_{elec} = 0.5\left(\frac{V_{C2}^{2}\, C_2}{G_{C2} - x}\right)$$

- Increasing the travelling distance will increase the resultant electrostatic force which is desirable for large force actuation
- The travelling distance was increased from 2.5 µm to 4.4 µm
- A corresponding bouncing maximum peak was increased from 112.5 nm to 400 nm
- The larger electrostatic force is the larger force actuation, but also the more impact of bouncing (Trade-off!)



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Conclusion

- Electrostatic actuator fabricated by silicon technology is potential approach for miniaturized inchworm motor
- Mechanical bouncing in terms of maximum peak and transient time influences critically the design of comb structure and switching signal characteristics such that even at low mechanical loading
- Large electrostatic force is desirable for large force actuation, but as the applied electrostatic force increases the bouncing effect increases too
- Applying two control signals at the two variable capacitor will be a potential approach for reducing the level of mechanical collision and thus reducing the bouncing effect on the actuation stability response

References

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Acknowledgements

This project is funded by the German Research Foundation (DFG) under the umbrella of the priority program SPP 2206 – KOMMMA (Cooperative Multistage Multistable Micro Actuator Systems).

KOMMMA

A DFG PRIORITY PROGRAMME

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