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Posted Date: 30 January 2025

doi: 10.20944/preprints202501.2201.v1

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Reduction of Microfluidic Logical Pneumatic Mono Stable-Oscillators' Reversible Outlet Flow

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Abstract: Microsystems have been developed for a wide range of applications, including medical, military, and industrial maintenance, driven by advancements in actuating and measuring systems. Fluidic actuators, known for their compactness, low cost, and energy efficiency, are increasingly recognized for their potential in cutting-edge industrial and medical microsystems. This study explores the transition from traditional actuators to innovative mono-stable oscillators designed specifically for flow regulation. Mono-stable oscillators have long been acknowledged as effective tools for controlling fluidic logic. These devices provide a control solution without movable components, though they exhibit non-zero reverse output flow—a limitation consistently observed in prior research. Passive solutions, such as Tesla diodes or convergent-divergent conduits, have proven insufficient to address this issue. In this work, we propose a novel approach to eliminate reverse flow by introducing a moving object within the outlet oscillator. Through simulation, we demonstrate that this method effectively mitigates recirculation, offering a significant improvement over existing designs. This study provides a promising solution to enhance the performance of fluidic actuators in microfluidic systems.

Keywords: microsystems; fluidic actuators; mono-stable oscillators; flow regulation; reverse flow; recirculation control; simulation modeling; fluidic logic; passive solutions; actuator design

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1. Introduction

Microfluidic technologies have experienced significant growth and development in recent years, emerging as one of the most rapidly advancing fields in scientific research. Among these technologies, microactuators have garnered considerable attention due to their critical role in regulating and manipulating various processes. The development of microactuators dates back to the late 1970s, and since then, there have been substantial advancements in the field of Micro-Electro-Mechanical Systems (MEMS) actuators, particularly in terms of efficiency, power, and force output. These advancements have made microactuators indispensable in emerging industrial and medical applications, where compact, cost-effective, and high-performance devices are increasingly sought after [1].

Fluidic microactuators, which utilize pressurized fluids—either gases (pneumatic) or liquids (hydraulic)—to induce motion through the deformation of inflatable chambers, have demonstrated exceptional power and force densities at the microscale [2]. Their notable durability and resistance to environmental factors further enhance their appeal. Despite these advantages, fluidic microactuators often receive less attention compared to other MEMS technologies, leaving significant potential for further exploration and innovation.

This study focuses on fluidic actuators, with particular emphasis on their operational principles, classifications, and characteristics. Fluidic actuators enable fluid motion through two primary mechanisms: (1) direct peristaltic motion induced by actuated solid membranes, or (2) indirect motion driven by hydrodynamic or osmotic effects. These mechanisms facilitate rotational,

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translational, and deflection motions, making fluidic actuators versatile tools for a wide range of applications.

One notable category of fluidic actuators is the amplifier fluidic actuator, which operates based on the Coanda effect. This effect ensures the attachment of the main jet from the supply flow to the wall, producing an output flow at the device's end. By altering the control flow or pressure, the main jet can be redirected to another output, achieving stable functionality. However, the process of jet attachment and switching is complex and has been the subject of extensive research [4,5]. These fluidic elements perform functions analogous to electronic systems, offering unique advantages in microfluidic applications.

Despite their potential, fluidic actuators face challenges, particularly in controlling reversible outlet flow in mono-stable oscillators. This study addresses this issue by proposing a novel approach to reduce reversible outlet flow, thereby enhancing the performance and reliability of microfluidic systems. The general design for a fluidic element from this category is presented in Figure 1

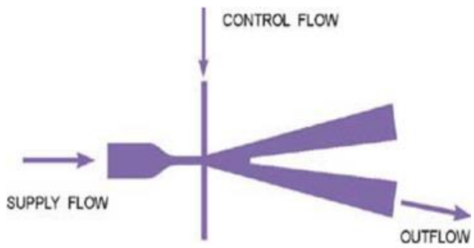

Figure 1. geometrical form of micro actuators.

This overview primarily examines fluidic actuators, with a particular emphasis on their operational principles, classifications (see Table 1), and distinguishing features.

Table 1. Relevant work on micro actuators.

reference	First Author	Year	Actuation Type	Size L*w*h (in µm)	Operating Conditions
[36]	Chi S.P.	1997	Electro thermal	1000*700*3	15V 2,8µN
[37]	Neils T.	1998	Electrostatic	200*100*0,5	40V
[38]	Just E.	1999	SMA	2000*3900*100	22mW 17mN
[39]	Bhailis D.	2000	Electromagnetic	5000*5000*2000	1A 15mN
[05]	Volland B.E.	2001	Electrostatic	3300*1250*5	80V 170µm Ø
[40]	Fuller, S.B.	2002	Electro thermal	/	300 °C 5V
[41]	Abadie J.	2002	SMA	3000*800*200	0,8A 68°
[25]	Bordatchev E.V.	2003	Electro thermal	2800*1400*12,5	1,9V
[42]	Olivier. M	2004	Electrostatic	1200*800*10	75V
[43]	Yang J.	2004	Piezoelectric	1200*320*1,5	15V 16,67kHz
[44]	Vitorio. A	2004	Electrostatic	/	400V
[33]	Zhang H.	2004	SMA	4000*3000*290	1A 81µm Ø
[45]	Ahn	2004	Electromagnetic	3500*3500	20mA 920Hz
[46]	Fu	2004	SMA	2200*2200	5V 30mA
[02]	D.Piyabongkarn	2005	Electrostatic	3200*3000*50	10V
[29]	C.T. Pan	2005	Electromagnetic	1000*1000*10	5V 17,5°
[31]	D.H. Kim	2005	Electromagnetic	15500*5220*500	8V 18mN
[47]	Mitsui	2006	Electromagnetic	7400*9800	4.6mA 80,5Hz
[13]	S.K.Nah	2007	Piezoelectric	36000*30000*3	0-100V
[06]	Felix. B	2007	Electrostatic	7700*5600*50	150V 100µm Ø
[48]	Liu X.	2007	Electrostatic	4000*4000	30V

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[49]	Young-ho C.	2007	Electromagnetic	4000*4000*570	27mA	11kHz
[50]	Andrew C.	2007	Electromagnetic	200*2*3.5	4V	200µN
[51]	Kim	2007	Electromagnetic	2400*2900	3V	350Hz
[52]	Vagia. M	2008	Electrostatic	400*400	/	
[07]	Chen. T	2008	Electrostatic	6200*3500*50	30V	150µm Ø
[53]	Gustavo.A.	2008	Electro thermal	500*500*30 1000*1000*30	70mW 79mW	
[54]	Guo S.	2008	SMA	45000*30000*30000	1000µL	50 Hz
[55]	P. M. Nieva	2008	Electro thermal	200*25*2	10V 3.7-13.3µm	
[08]	Varona. J	2009	Electrostatic	100*100*3,5	45V	
[56]	Jia	2009	Electro thermal	1000*1000	8V	336Hz
[57]	Micky.R.	2010	Piezoelectric	15000*2000*300	100V	15mN
[58]	Zhu	2011	Piezoelectric	2000*2000	2V	316Hz
[16]	Koh	2011	Piezoelectric	5000*5000	9V	30Hz
[59]	Lan C.C.	2011	SMA	45000*70000*20500	3.6 V	490mN
[60]	Liu	2012	Electro thermal	2000*2000	0,6V	197Hz
[09]	Jia. Y	2013	Electrostatic	6900*6500*50	120V	
[61]	Q. Xu	2013	Piezoelectric	26000*5000*860	2V	500Hz
[62]	Park, E.S.	2013	Electrostatic	650*90*2.25	200°C	10Ω
[63]	Ren-Jung Chang	2013	SMA	937*477	50mA	3V
[64]	Bessonov, A.	2014	Piezoelectric	25000*1000*6.6	/	
[65]	A. Sharma	2015	Piezoelectric	7100*2300*566	114Hz	54nW
[66]	Salem Saadon	2015	Piezoelectric	2450*780*512	0,4V	6,8µW
[67]	Hussein hussein	2015	Electro thermal	3200*400*100	15V	18V
[68]	Marija Cauchi	2016	Electro thermal	411*45*4	0,22V	9µm Ø
[69]	Bruno Andò	2016	Electromagnetic	95000*20000*140	4.1 Hz	37.1 mT
[70]	Yuki Yamamoto	2016	Electrostatic	10000*10000*38	38mg	
[71]	Haijun Zhang	2017	Electro thermal	580*105	13.7 µm	2 Hz
[72]	Achraf Kachroudi	2017	Piezoelectric	20000*20000*150	d33=750 at 25°C	
[73]	Yingxiang Liu	2018	Piezoelectric	80800*48000*24000	427 mm/s	
[27]	Marija Cauchi	2018	Electro thermal	606*169*28	3V	(5-9)µm
[74]	Ying Wu	2019	Piezoelectric	12000*10000*8000	5.86 x 105 µrad/s	
[28]	Rolend Elsen	2019	Electro thermal	/	1V	(55-110) µm
[75]	Palak Bhushan	2020	Electromagnetic Actuator	4cm and weighs 133 mil-gr	voltage (<3 V)	
[76]	Fan, J.	2020	Pneumatic actuator	175000 × 100000 × 60000	0.01 to 0.09	
[77]	Nader A. Mansour	2021	Electromagnetic Actuator	15000 × 15000 × 40 000	0 to 100 mA	
[78]	Cheng, P.	2021	Vacuum buckling	220000	−0.002 to −0.1 MPA 0.6 to 2 HZ	
[79]	Saurabh .Jadhav	2023	Pneumatic actuators	60000 x60000		

2. Simulation of Fluidic Actuation with Mobile Object

The increasing demand for microsystems in medical and military applications has driven the development of advanced actuation systems. In this study, we simulate mono-stable fluidic systems incorporating mobile components to manipulate the shape and output chamber of the moving object, thereby optimizing actuator performance.

Description of the Geometrical Model (Combination of Oscillator and Actuator)

A fluidic actuator measuring 5 × 15 mm² was designed for numerical simulation using FLUENT. The actuator features a moving part with two inlets and one outlet. To evaluate the system's behavior

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and optimize performance, the moving part was modeled in three distinct shapes: sphere, square, and H-shaped, each with dimensions of 4.8 mm.

The simulation process involved the following steps:

1-Geometrical Modeling: The actuator and oscillator were combined into a single model.

2-Mesh Generation: A triangular mesh was created, consisting of 166,782 nodes, to ensure accurate simulation results.

3-Dynamic Mesh Model: A dynamic mesh model was employed to track the movement of the mobile object under fluid forces.

4-The geometry of the actuator was modified to ensure convergence at the two inlets, aligning with the oscillator's outlet dimensions. This configuration is illustrated in Figure 2

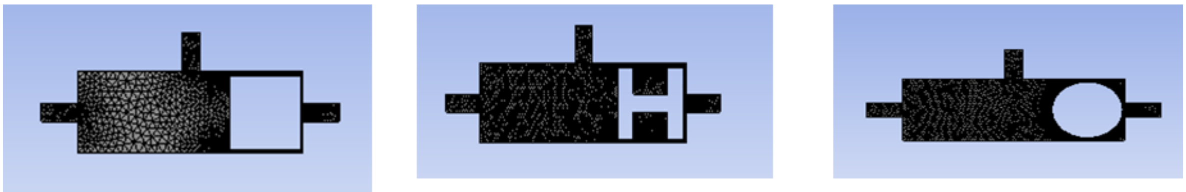

Figure 2. Geometrical form and meshing prototype.

The second part of this study constitutes its core contribution. It involves the integration of the ball actuator with the fluidic oscillator to enhance the oscillator's performance by minimizing reverse fluid flow through the right and left outlet holes, as well as the oscillator itself. To achieve this, the actuator's geometry was modified to ensure convergence at the two inlets, aligning it with the oscillator's outlet dimensions. This modified geometry is illustrated in Figure 3

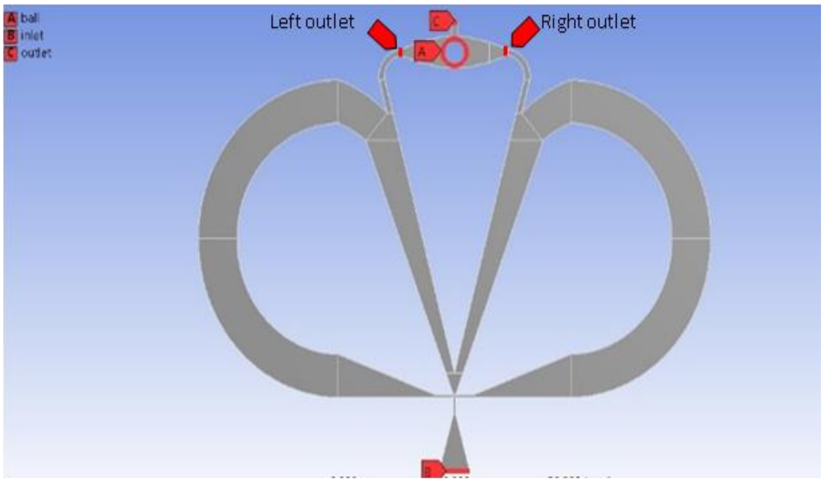

Figure 3. The geometry representing the combination of the actuator and the oscillator.

To accommodate the new geometry, several modifications were made to the mesh. The primary objective was to achieve a mesh with a low maximum aspect ratio and minimal asymmetry. The final mesh used in the FLUENT simulations, presented in Figure 4, consists of a triangular structure comprising 166,782 nodes. To ensure optimal balance between result accuracy and computational efficiency, additional meshes with varying densities (41,000 nodes and 442,986 nodes) were also generated and evaluated.

As the moving part (the sphere) shifts in response to fluid forces acting on its boundaries, the mesh boundaries must adapt accordingly. To address this, a dynamic mesh model was employed. The dynamic mesh capabilities of FLUENT, combined with a user-defined function, were utilized to accurately track the movement of the sphere throughout the simulation.

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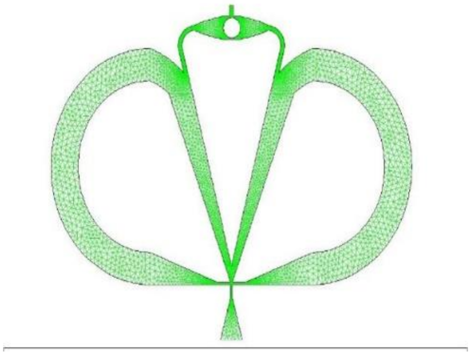


Figure 4. The mesh used for the simulations of geometry in Fluent.

3. Simulation Results

The mass flow rate at the exit of the actuator, corresponding to the geometry of case (b), is depicted in Figure 5. This figure illustrates the mass flow rate under a pressure variation of P = 3 bar during both the forward and return motion of the spherical mobile object Figure 6..

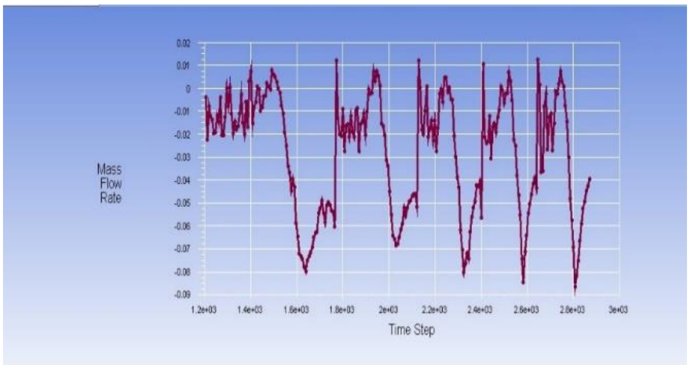
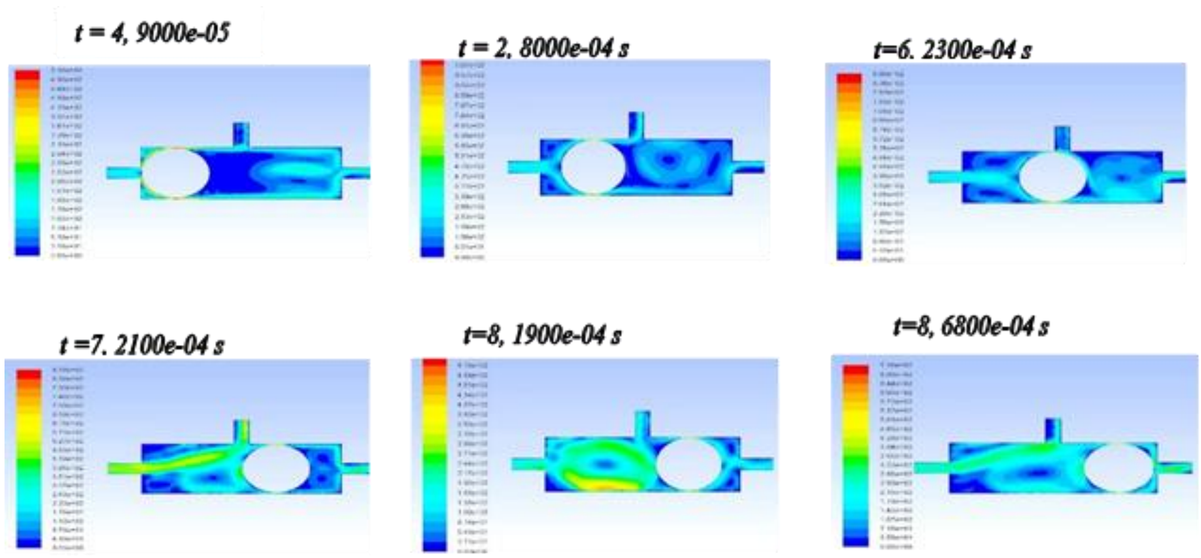


Figure 5. Mass flow rate signal as a function of time (s) at the output and for a ΔP = 3 bar at the output of the actuator for the circular-shaped mobile.



Mobile Forward phase

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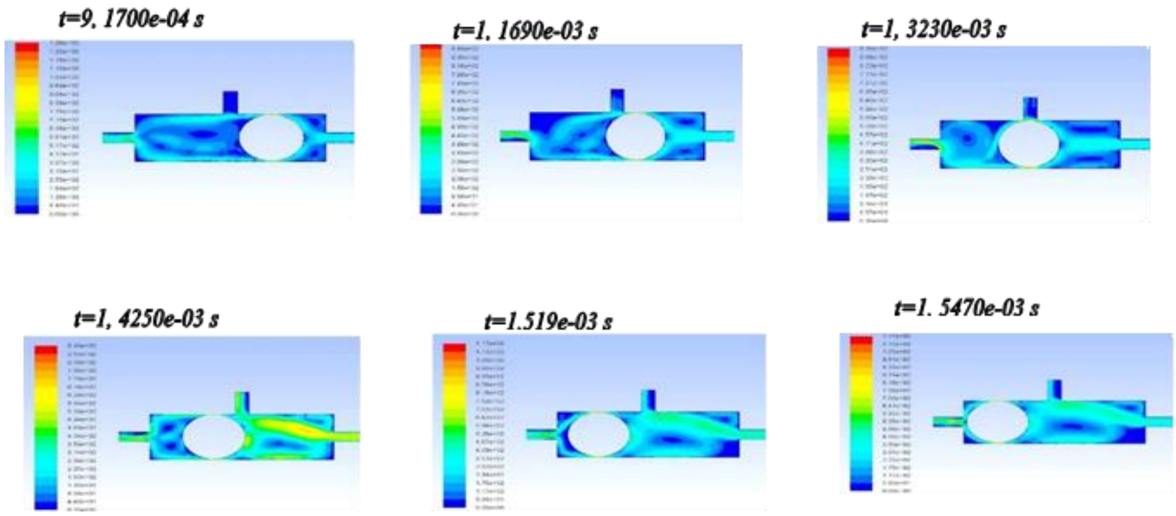

Mobile return phase

Figure 6. Contour plots of the velocity Position of the ball at different times.

3.1. Evolution of Mass Flow at the Left and Right Outputs of the Oscillator-Actuator Combination

Figure 7 depicts the mass flow rate as a function of time at the actuator's output under applied pressures of 2 bar and 2.5 bar, respectively. The results indicate that the return flow at both the left and right outputs of the oscillator is nearly negligible.

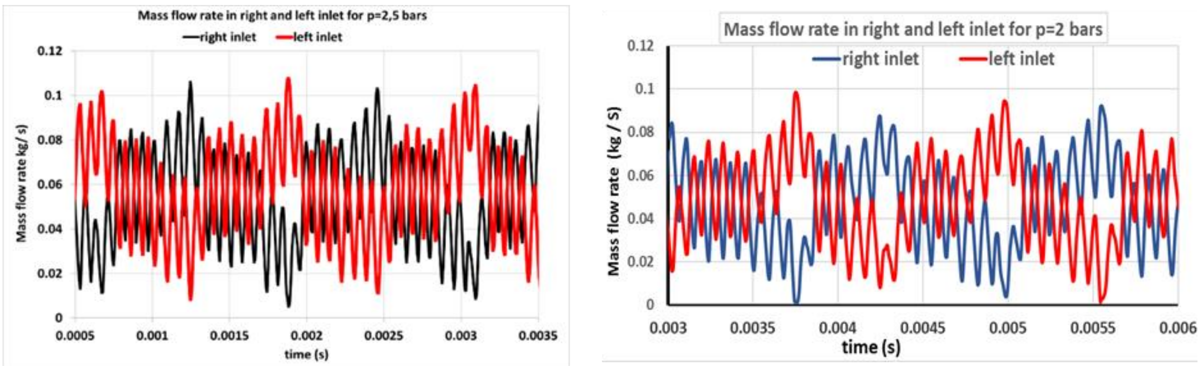

Figure 7. Mass Flow Rate Signal as a Function of Time at the Right and Left Outlets for the Oscillator-Actuator Combination Subjected to Pressures of 2 Bars and 2.5 Bars.

3.2. Evolution of Mobile Velocity

Figure 8 illustrates the axial velocity profiles of the sphere's motion for supply pressures of P=1.5 bar and P=2 bar at the oscillator inlet. The profiles exhibit a distinct sawtooth pattern, with the velocity reaching a peak of 10 m/s at a pressure of 2 bar.

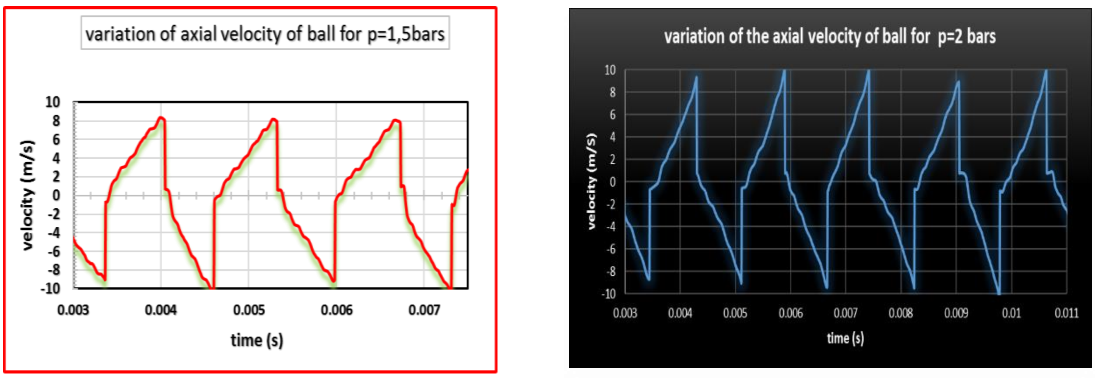

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Figure 8. Axial Velocity Profile as a Function of Time for Pressures P=1.5 barP = 1.5 \, \text{bar}.

3.3. Trend Curve

The fluid oscillator frequency at the millimeter scale was simulated using CFD. The initial numerical results indicate that the fluid oscillator frequency increases with an increasing ΔP/P ratio, within a pressure range of 1.5 to 3 bars Figure 9.

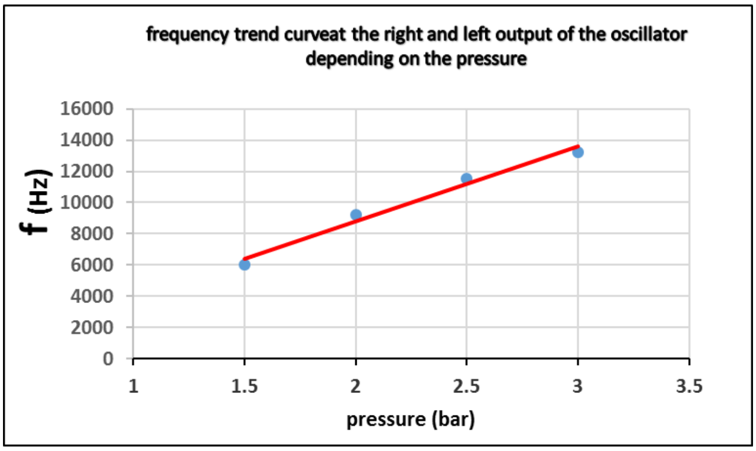

Figure 9. Trend Curve Representing the Oscillation Frequency as a Function of the (ΔP/P).

5. Conclusions

The performance and compactness of microfluidic actuators have been significantly enhanced through the implementation of various mechanisms and innovative combinations. High-performance actuators, characterized by their elevated force and power density alongside minimal power consumption, are in great demand for a wide range of applications, including minimally invasive surgical procedures and micro-robotic systems.

Numerical simulations have been conducted to assess the efficiency of these microactuators, with particular attention given to the internal channel length scale and the diameter of the digital flow. However, accurately modeling the complexity of the diode geometry remains challenging due to the involvement of high-pressure conditions.

This study has proven to be instrumental in addressing several challenges faced by our team. Notably, it has provided effective solutions to the backflow issues encountered with mini-injectors, as reported in previous works in literature.

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