Performance enhancement of an accelerometer using intelligent technique

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Objective of this project

- **Objective**
  - To improve the linear range and sensitivity of a capacitive accelerometer
- **Previous Work done**
  - Modelling and simulation of accelerometer in open loop and closed loop with PID tuned using Ziegler-Nichols
- **Work Done in this project**
  - Accelerometer in closed loop with PID tuned using GA and Fuzzy PI+PD tuned using GA
- **Improvement**
  - Improvement in linear range(from 20 g to 50 g) and ITAE value (by 10 times)

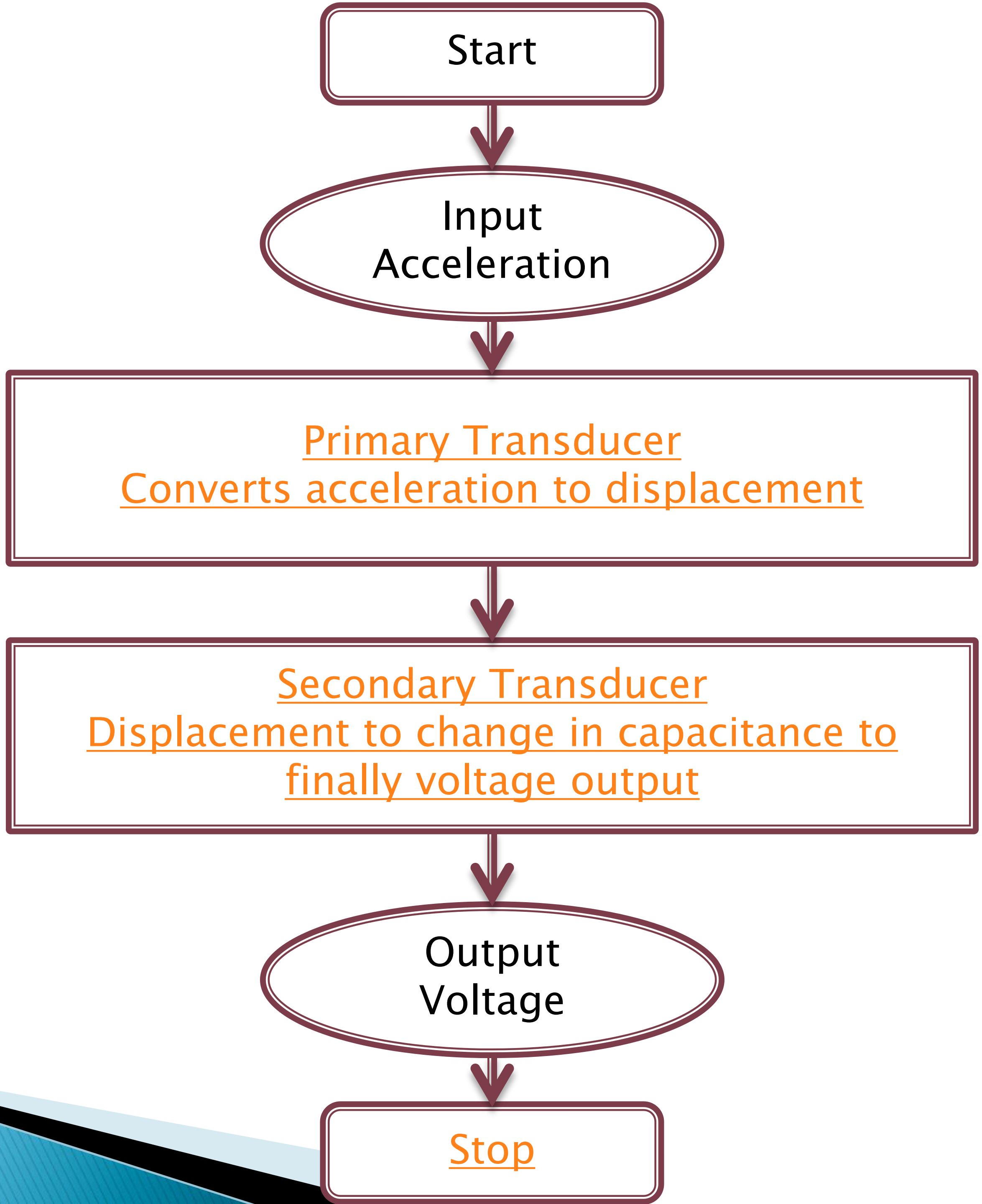
Accelerometer – INTRODUCTION

Accelerometer

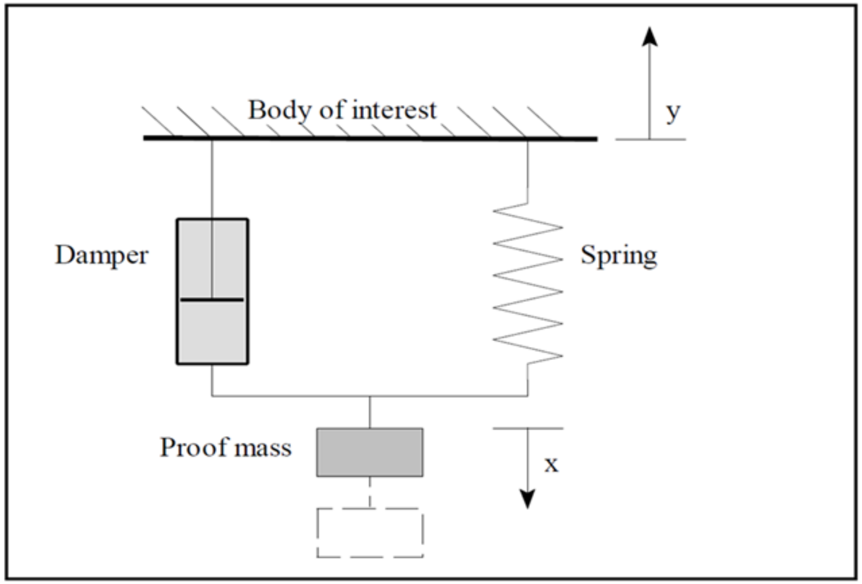
- Accelerometer is a device used for measuring:
  - Static Acceleration
  - Dynamic Acceleration
  - Velocity and Position

- Types
  - Capacitive
  - Tunneling
  - Piezoresistive
  - Piezoelectric

Capacitive Accelerometer– Open Loop


Start
Input Acceleration
Primary Transducer
Converts acceleration to displacement
Secondary Transducer
Displacement to change in capacitance to finally voltage output
Output Voltage
Stop

Primary Transducer



- The primary transducer consists of a
1. proof mass which is suspended by a
2. spring
- The acceleration causes a force to act on the mass which is consequently deflected by a distance 'x'.

- The motion equation of the proof mass is given by:

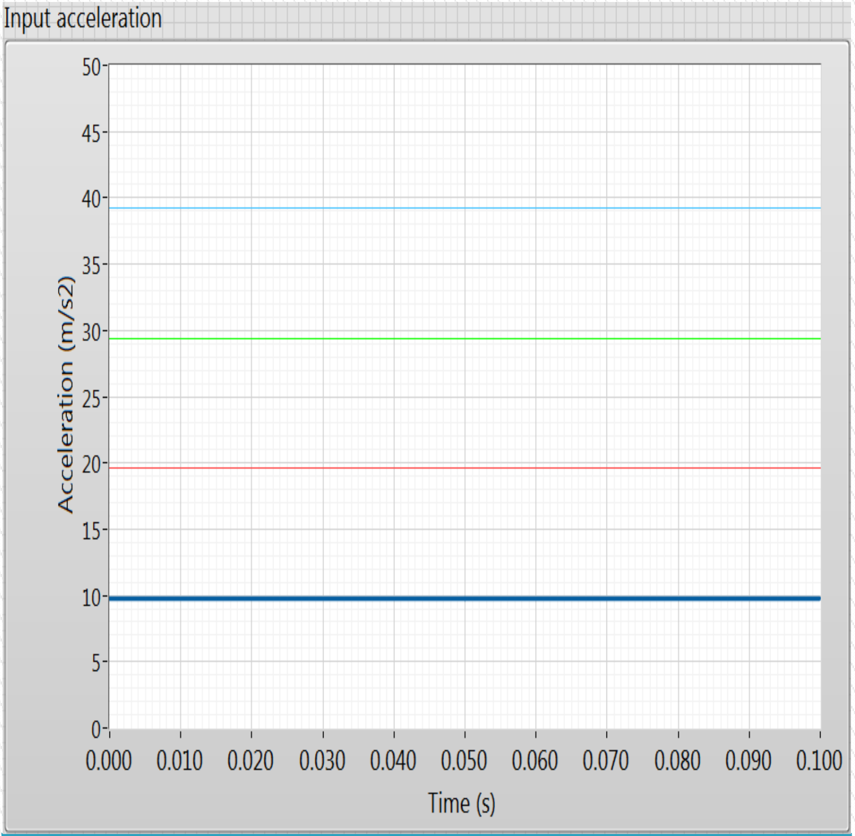
$$m\frac{d^2y}{dt^2} = m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx$$

where:
m: mass of the proof mass y: movement of the body of interest
x: movement of the proof mas b:damping factor
k:spring constant.
Here b is the reason for non linearity given as

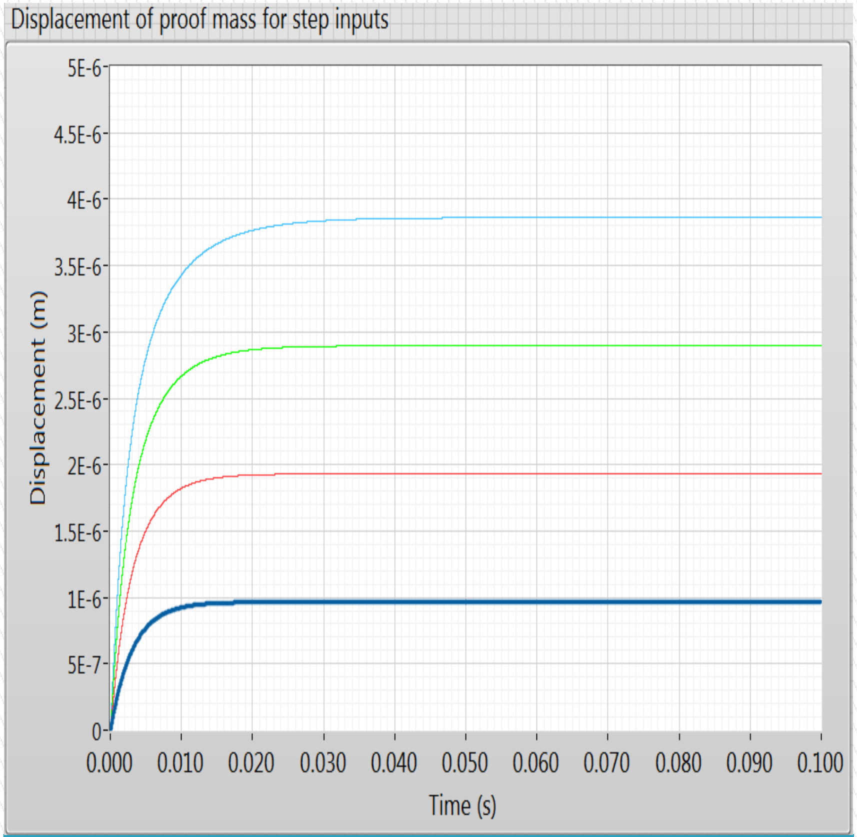
$$b(x) = \frac{1}{2}\mu A^2\left[\frac{1}{(d_0-x)^3} + \frac{1}{(d_0+x)^3}\right]$$

Displacement of proof mass

$$g = 9.8\ m/s^2$$



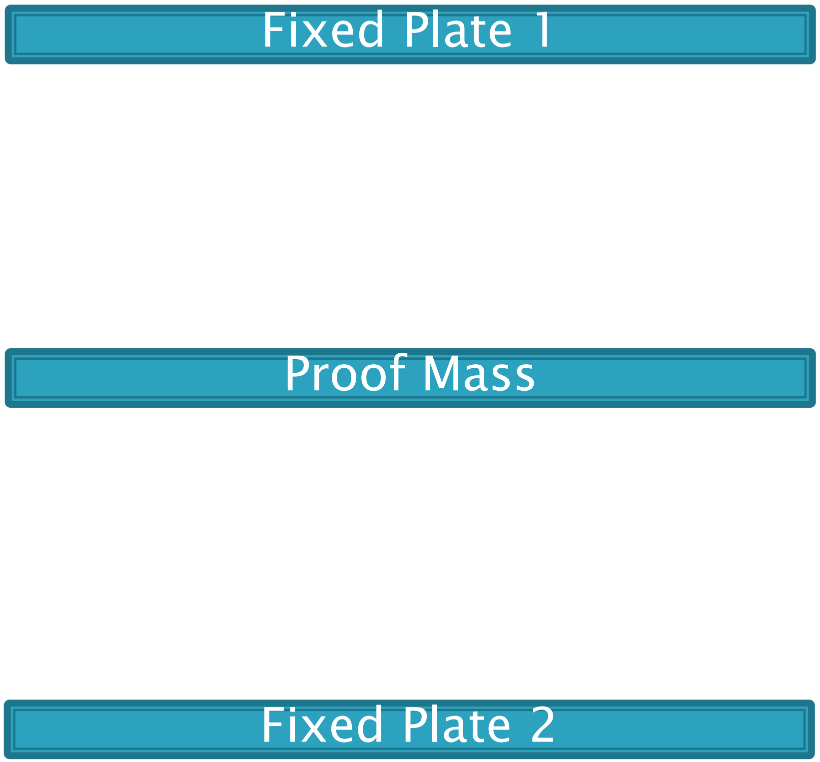
Input acceleration of 1g,2g,3g and 4g.



Displacement of proof mass for inputs of 1g,2g,3g and 4g.

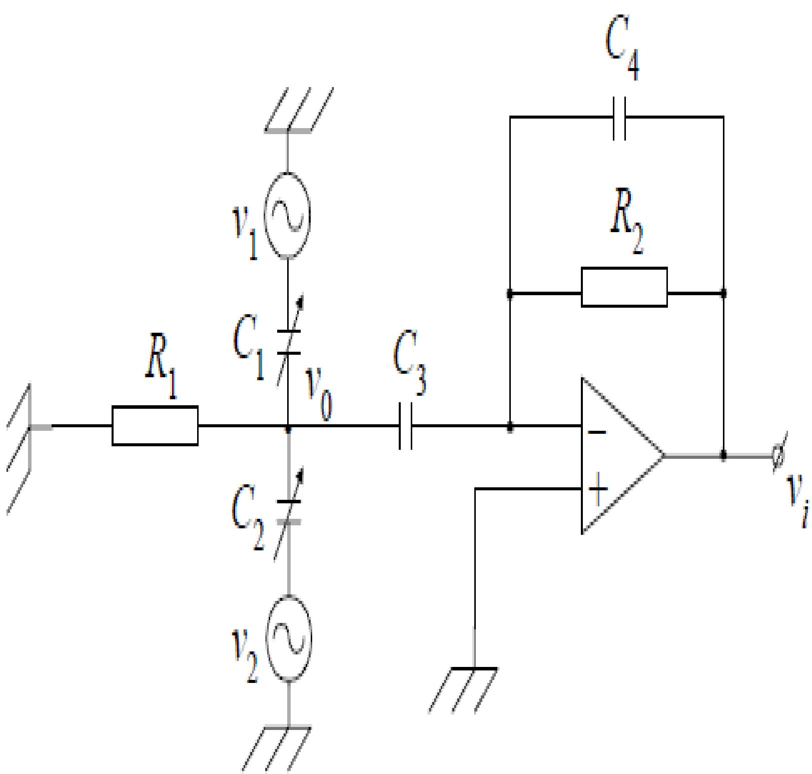
Secondary Transducer– Principle

C_1 is capacitance between fixed plate 1 and proof mass
C_2 is capacitance between proof mass and fixed plate 2



- Initially $C_1 = C_2$ when input acceleration is zero.
- When acceleration acts inertial force acts and proof mass moves thereby changing C_1 and C_2 .
- Now this change in capacitance is measured as a voltage signal using half bridge circuit

Secondary Transducer– Circuit

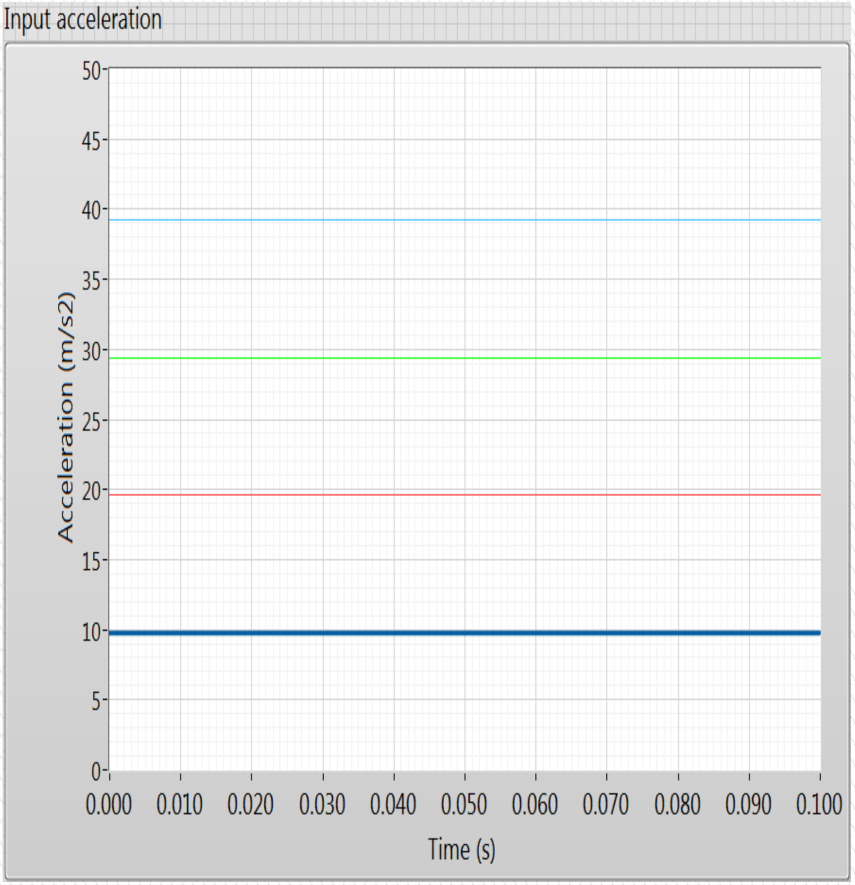


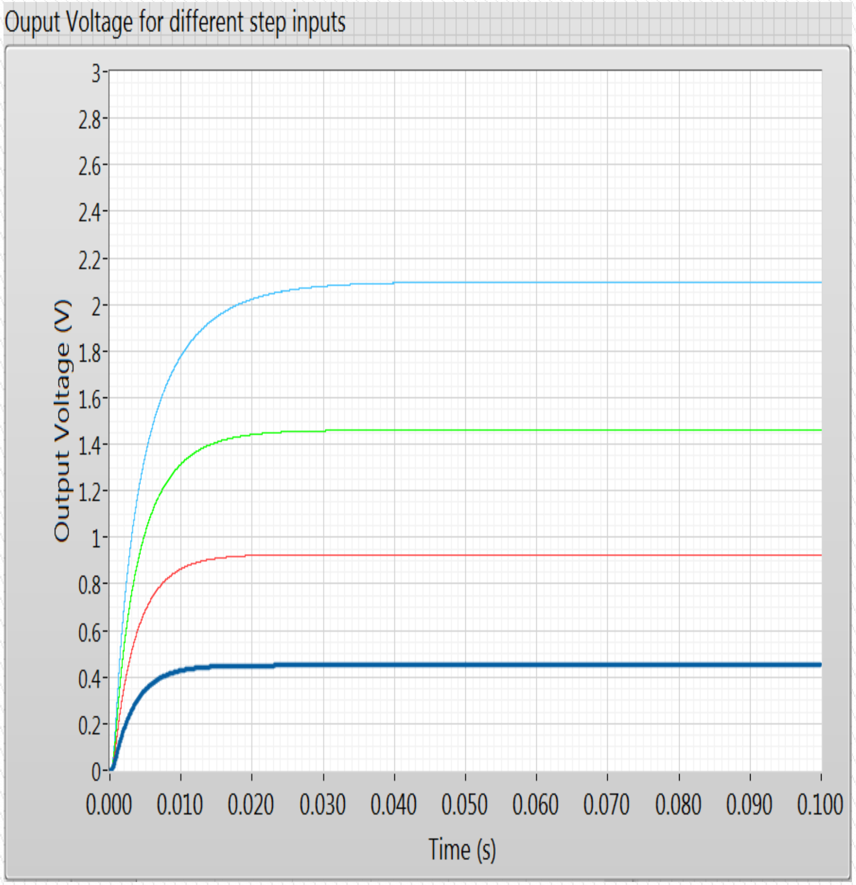
Detection device with charge amplifier

- v_1 and v_2 are voltage applied on fixed plate 1 and fixed plate 2 respectively,
- v_o is voltage on proof mass and
- v_i output voltage of amplifier
- When $C_1 = C_2$ voltage output is zero
- When $C_1 \neq C_2$ output voltage is given as

$$v_i = \frac{2s^2 C_3 R_2 \Delta C v_1(s)}{(1 + sC_4R_2)(s(2C_0 + C_3)1 + \frac{1}{R_1})}$$

Output Voltage





Input acceleration of 1g,2g,3g and 4g.

Output voltage for inputs of 1g,2g,3g and 4g.

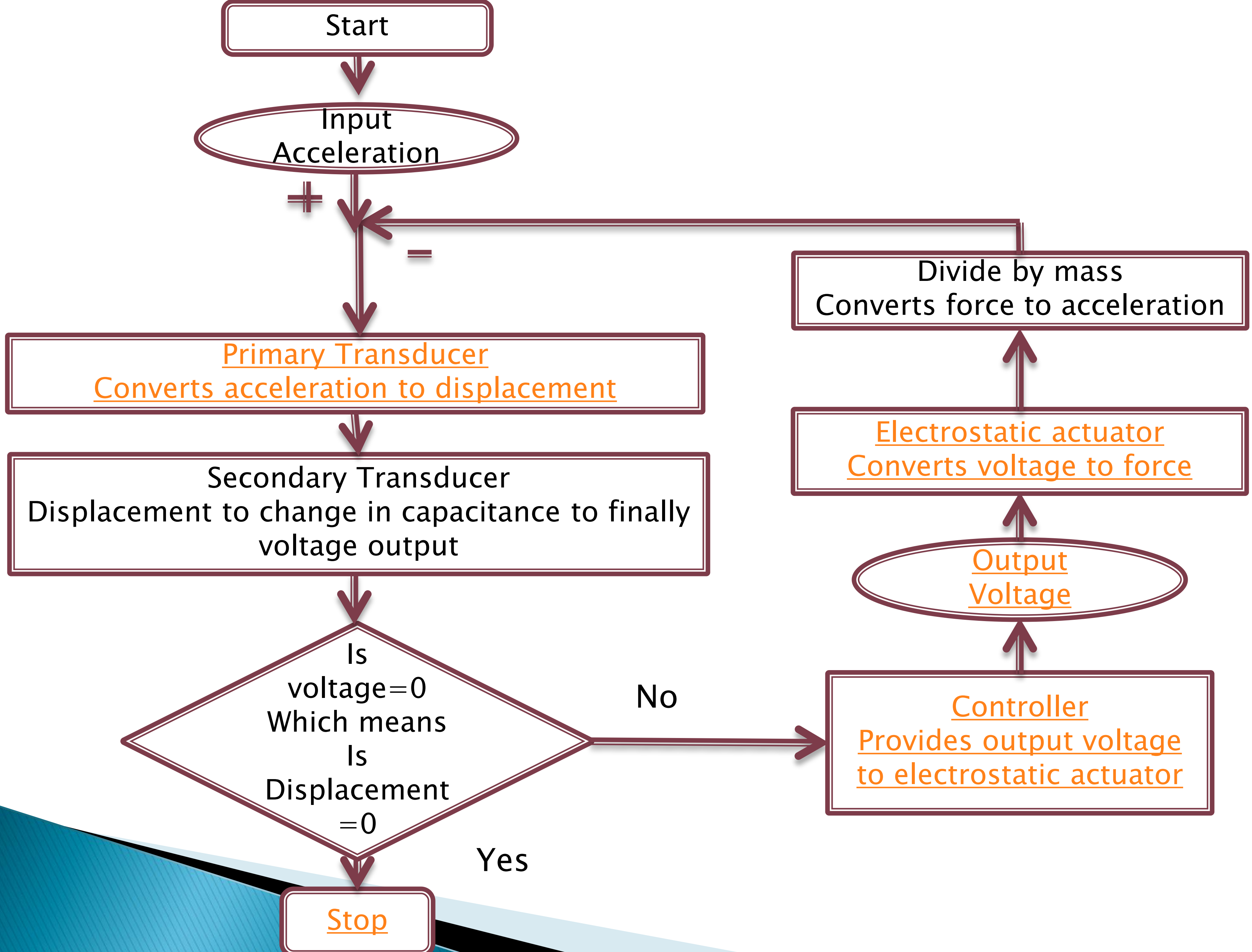
Parameters value

Mass of proof mass(m)	8.2 mg
Distance between fixed plates ($2d_0$)	20 um
Viscosity of air(u)	1.8E-5 Ns/m2
Amplitude of sinusoidal voltage applied to fixed electrode(V_1)	0.5 V
Area of plate(A)	12 mm2
Permittivity of air(E_0)	8.854E-12
R1	250 ohm
C4	22pF
R2	820K ohm
C3	1nF
C0	10.6pF
k_A	1.56
a2	72.9E-9
a1	0.3888E-3

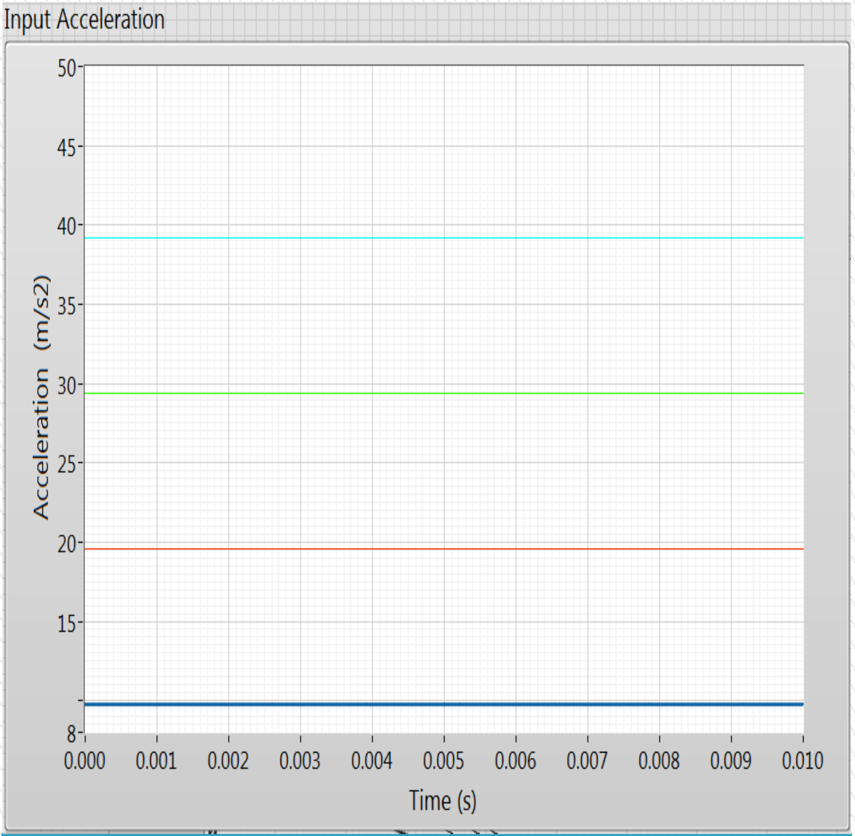
Issues with open loop mode

- Nonlinearity is dependent on displacement of proof mass
- For open loop we have large proof mass displacement so linear range is 0 to 4g
- Sensitivity depends on the output for a given input
- For open loop the output voltage is low
- So we go for Closed loop to have better linear range and output voltage

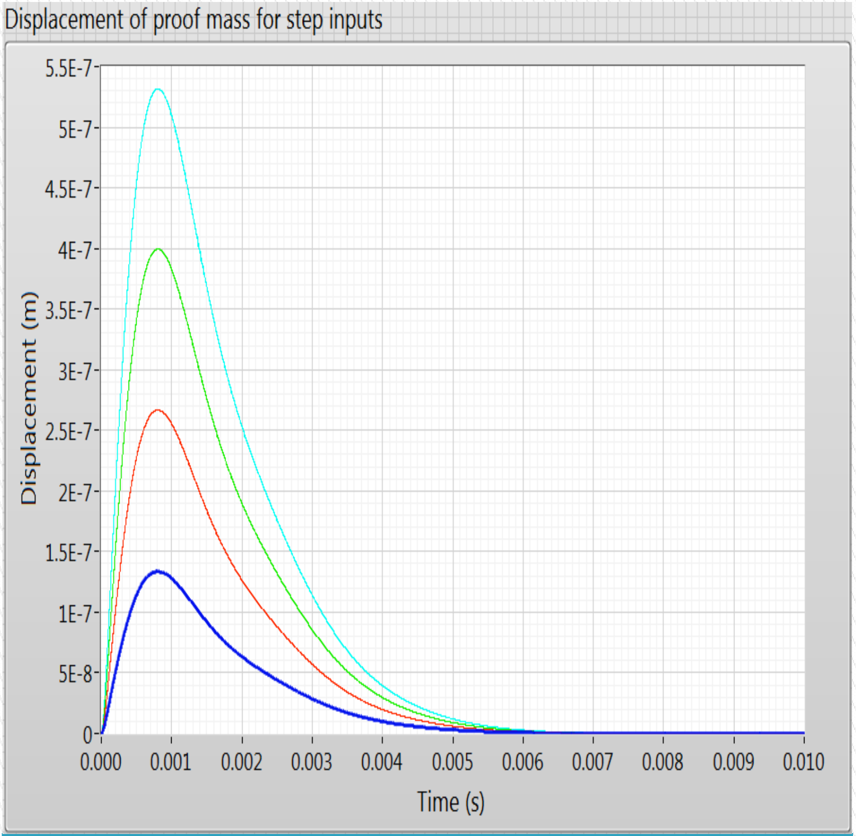
Capacitive Accelerometer– Closed Loop


Start
Input Acceleration
+
−
Primary Transducer
Converts acceleration to displacement
Secondary Transducer
Displacement to change in capacitance to finally voltage output
Is voltage=0 Which means Is Displacement =0
No
Yes
Stop
Controller
Provides output voltage to electrostatic actuator
Output Voltage
Electrostatic actuator
Converts voltage to force
Divide by mass
Converts force to acceleration

Displacement of proof mass for PID tuned using Ziegler-Nichols

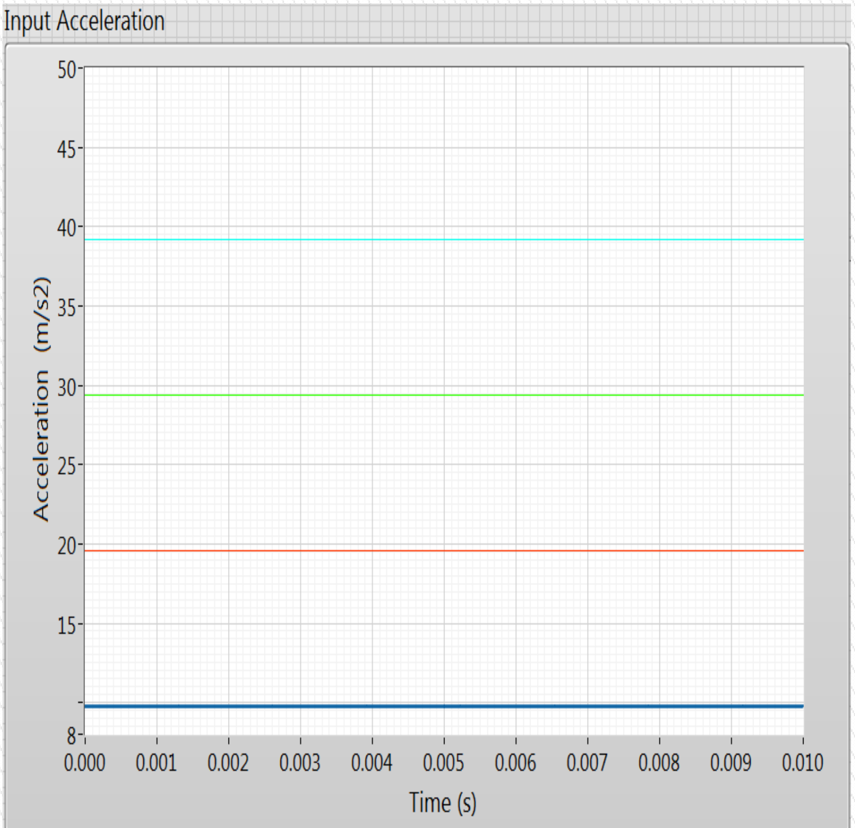


Input acceleration of 1g,2g,3g and 4g.

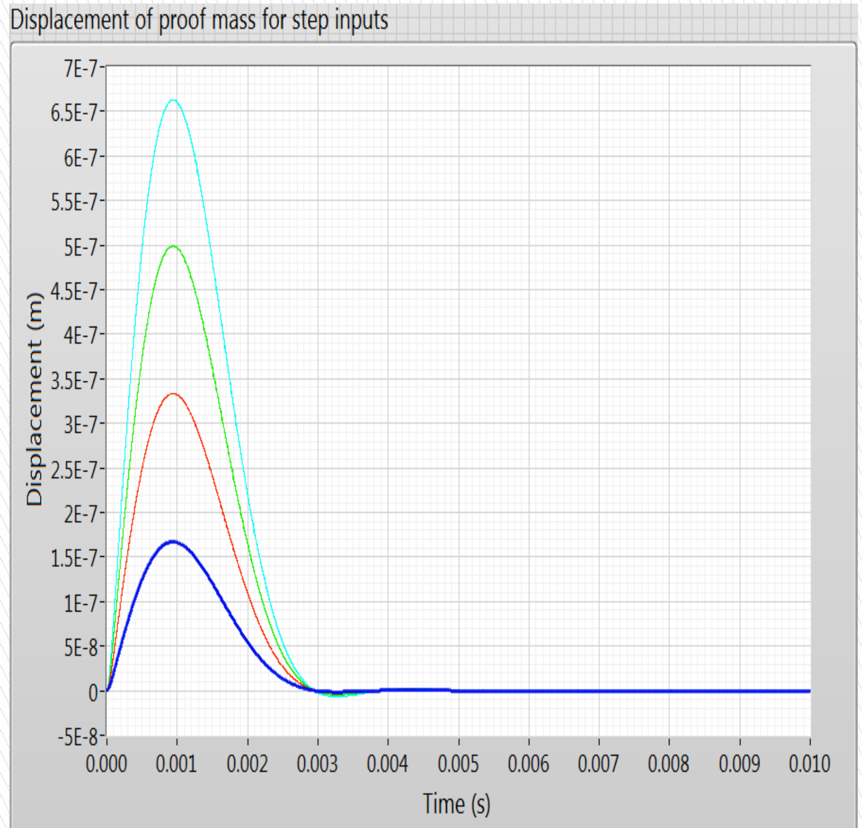


Displacement of proof mass for inputs of 1g,2g,3g and 4g.

Displacement of proof mass for PID tuned using GA

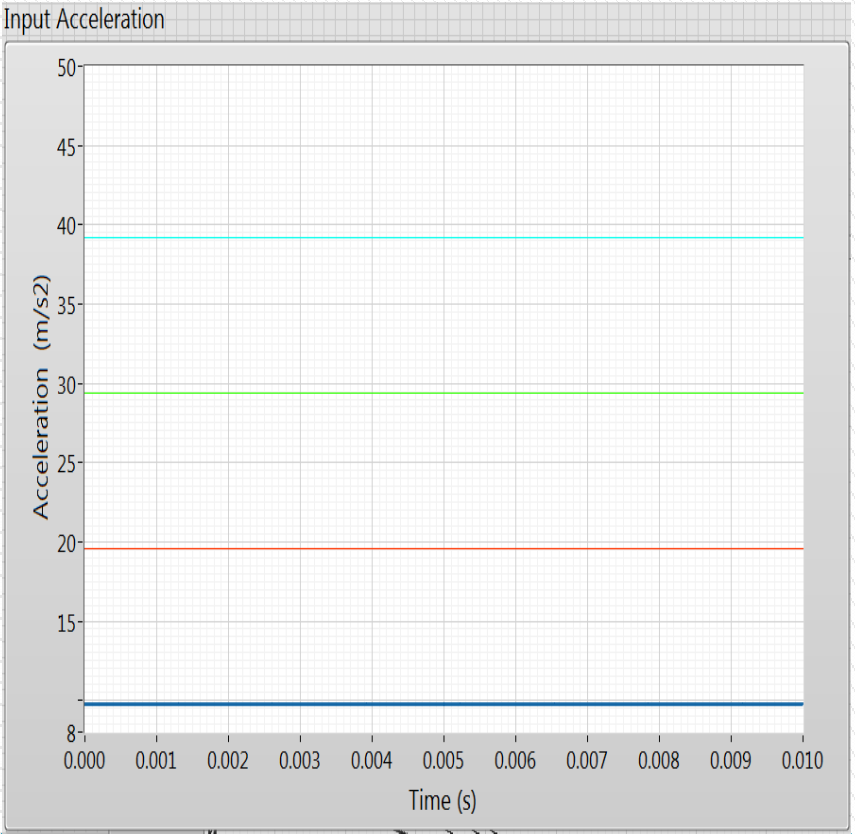


Input acceleration of 1g,2g,3g and 4g.

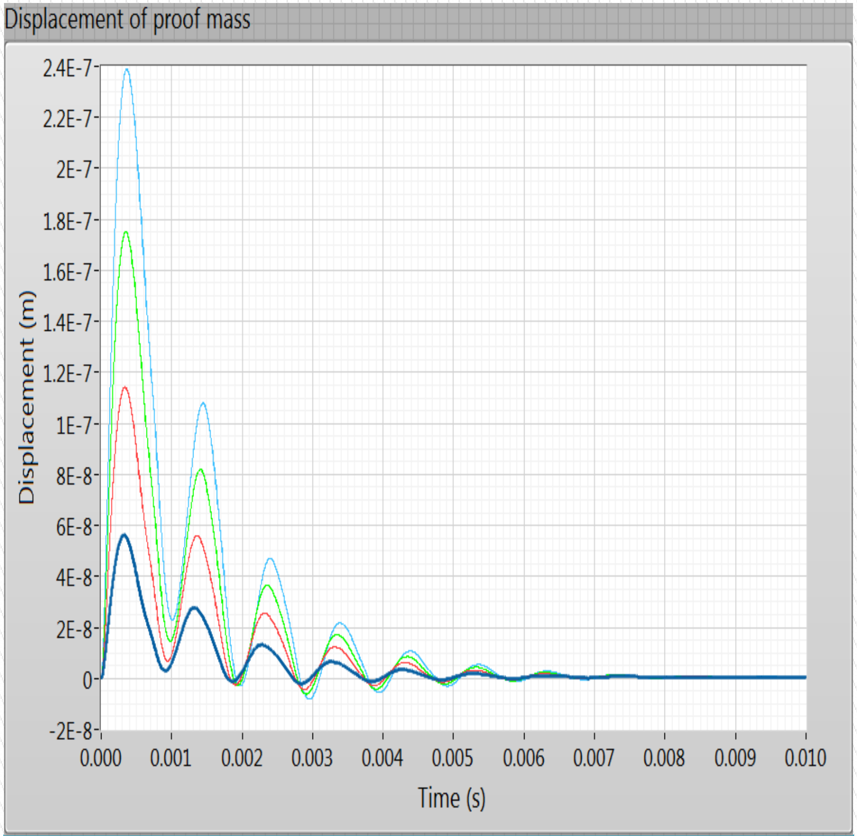


Displacement of proof mass for inputs of 1g,2g,3g and 4g.

Displacement of proof mass for Fuzzy PI + Fuzzy PD tuned using GA

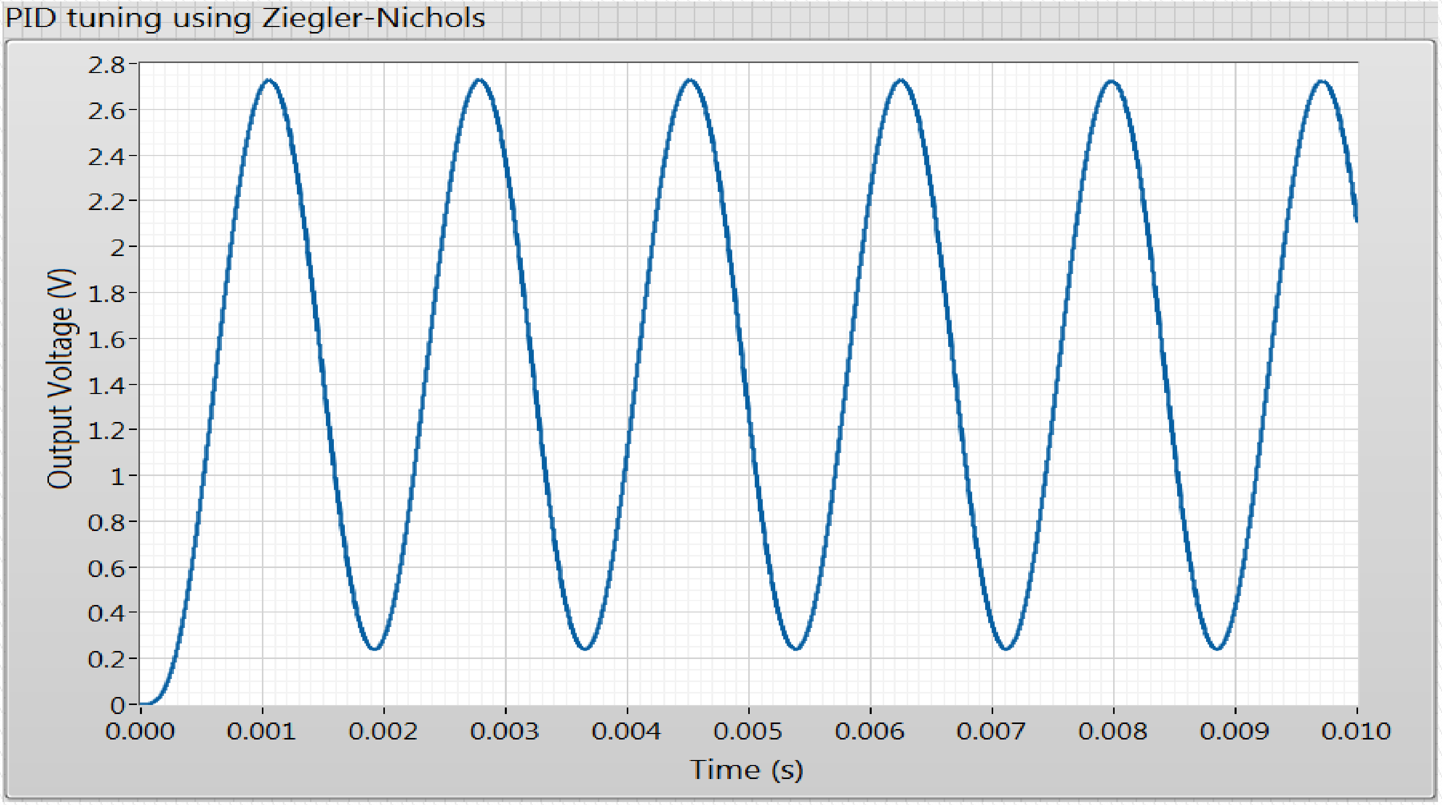


Input acceleration of 1g,2g,3g and 4g.



Displacement of proof mass for inputs of 1g,2g,3g and 4g.

PID Tuning



Using Ziegler Nichols the PID parameters are

$K_{P0} = 50$ and $T_0 = 2x10^{-3}s$

which gives

$K_P = 22, K_I = 13200$ and $K_D = 5.28x10^{-3}$

GA Tuning

- The objective of the GA was to minimize the ITAE (Integral of the Time weighted Absolute error) is given as:

$$ITAE = \int_0^\infty t|e(t)|\,dt$$

- But the GA finds the maximum value of a fitness function. So we used the following fitness function to minimise ITAE:

$$Fitness\ Function = \frac{1}{0.001 + ITAE} = \frac{1}{0.001 + \int_0^\infty t|e(t)|\,dt}$$

Fuzzy Logic Controller

- Fuzzification
  - For the experimentation, the inputs and outputs were quantized into 5 fuzzy sets, namely:

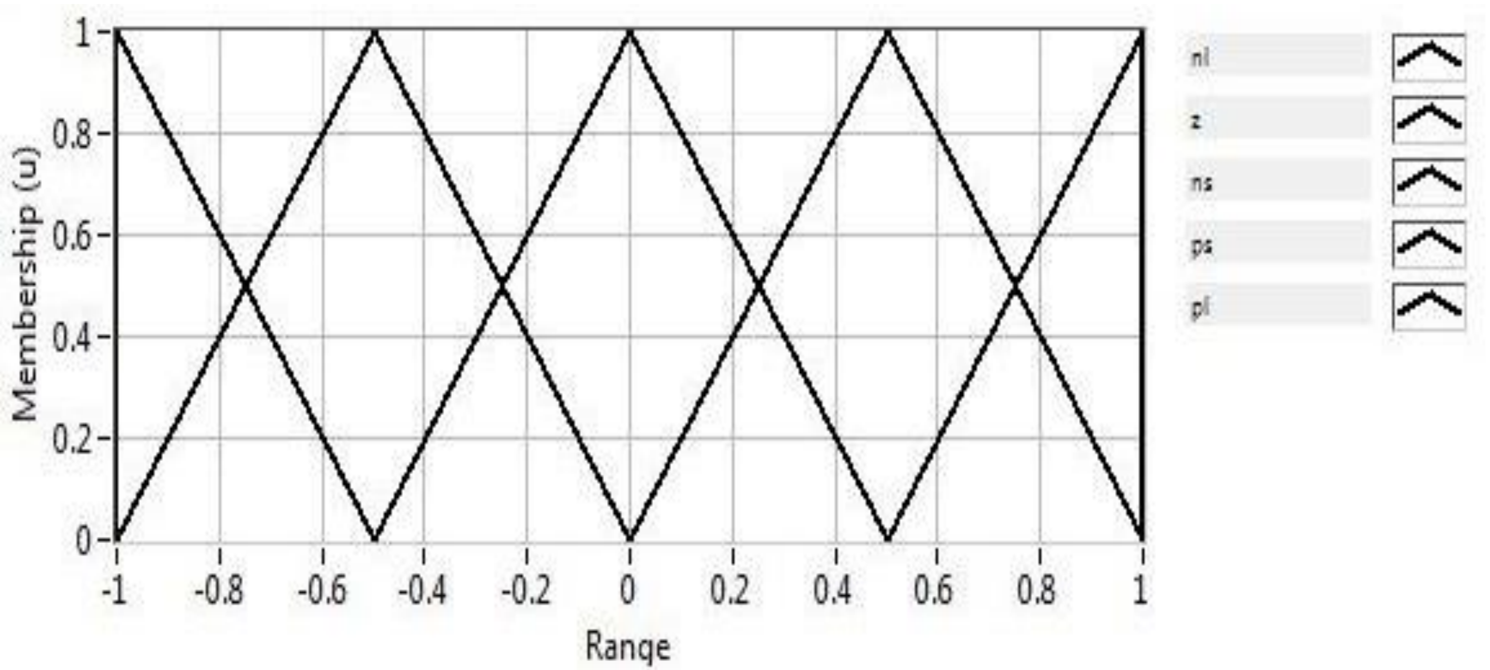
PL – Positive Large

PS – Positive Small

Z – Zero

NS – Negative Small

NL – Negative Large



Fuzzy Rule Base

Error (e)		Change of error (de)				
		NL	NS	ZE	PS	PL
	NL	NL	NL	NL	NS	ZE
	NS	NL	NL	NS	ZE	PS
	ZE	NL	NS	ZE	PS	PL
	PS	NS	ZE	PS	PL	PL
	PL	ZE	PS	PL	PL	PL

- **Inference Method**

  Mamdani's max min inference method was used for the Fuzzy Logic Controller Design.

- **Deffuzification**

  The center of gravity method was used for deffuzification.

- **Control Equation of Fuzzy PI + Fuzzy PD controller**

$$u_{PID}(k) = u_{PI}(k) + u_{PD}(k)$$

Where $u_{PD}(k) = K_c e(k) + K_D \Delta e(k)$ and

$$u_{PI}(k) = \frac{K_{UPI}}{1 - z^{-1}} \Delta u_{PI}(k)$$

where

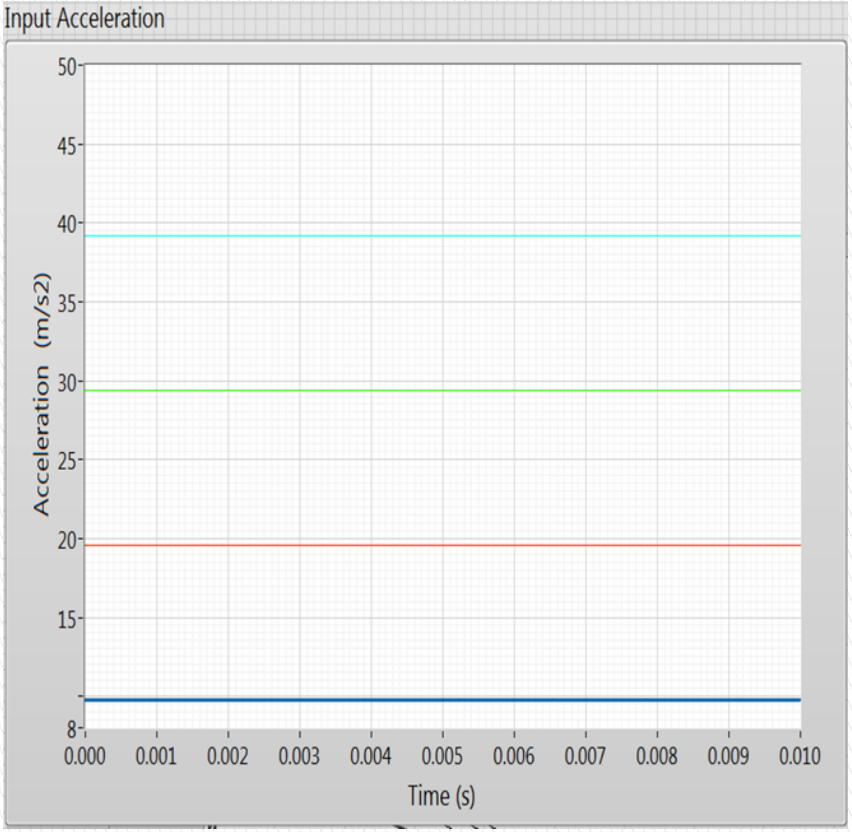
$$\Delta u_{PI}(k) = K_C \, \Delta e(k) + K_I e(k)$$

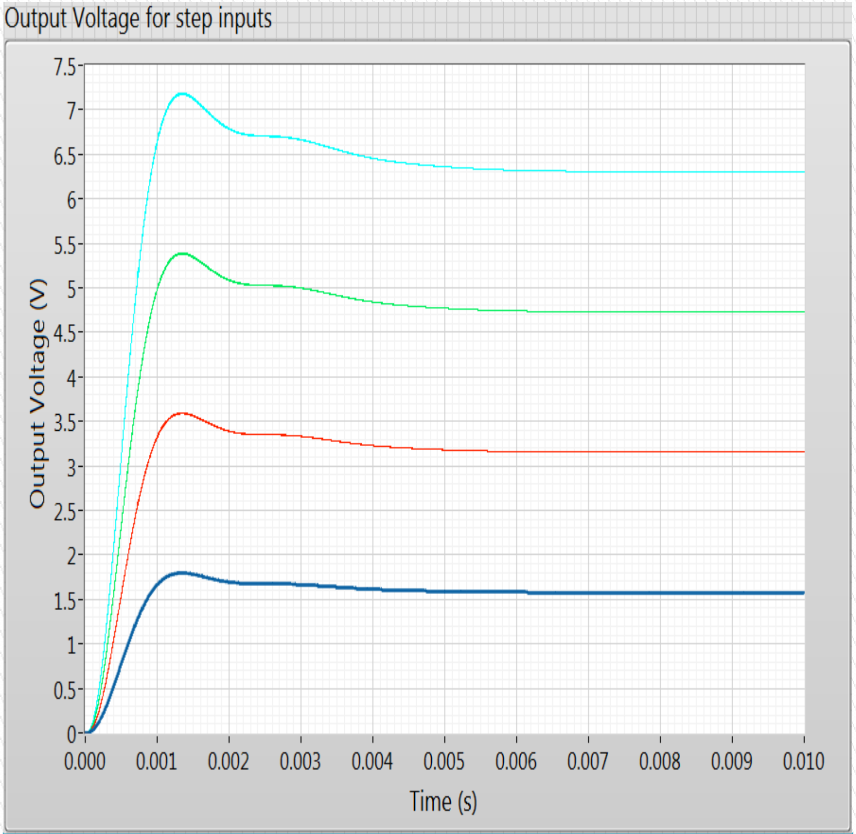
$e(k)$ *is error*

$\Delta e(k)$ is change in error

K_c, K_D, K_I and K_{UPI} are gains

Output Voltage for PID tuned using Ziegler-Nichols

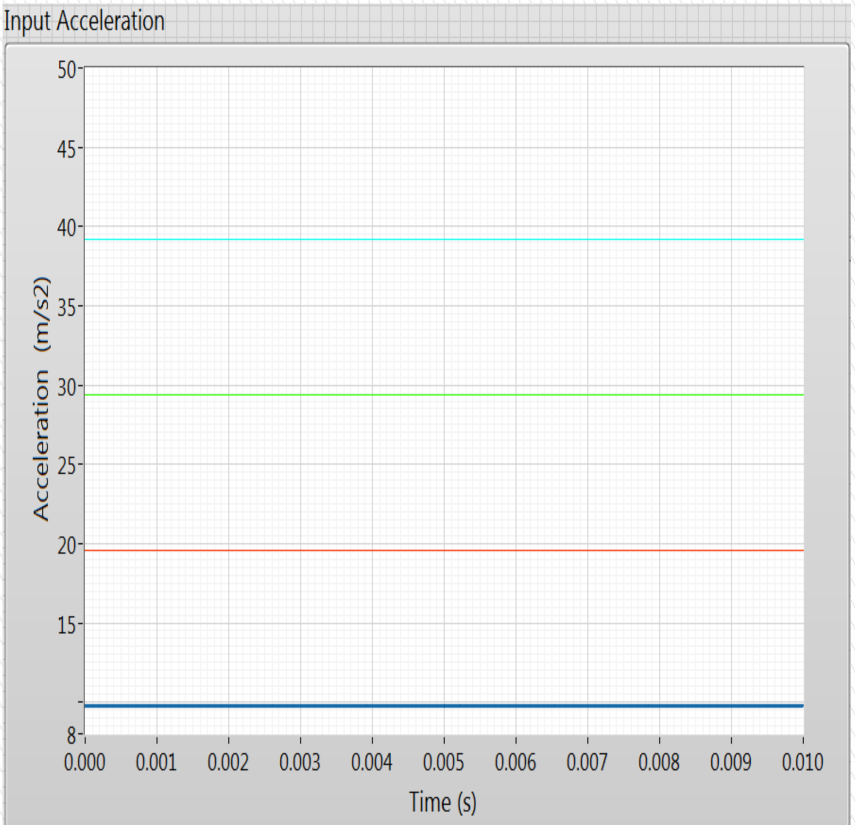




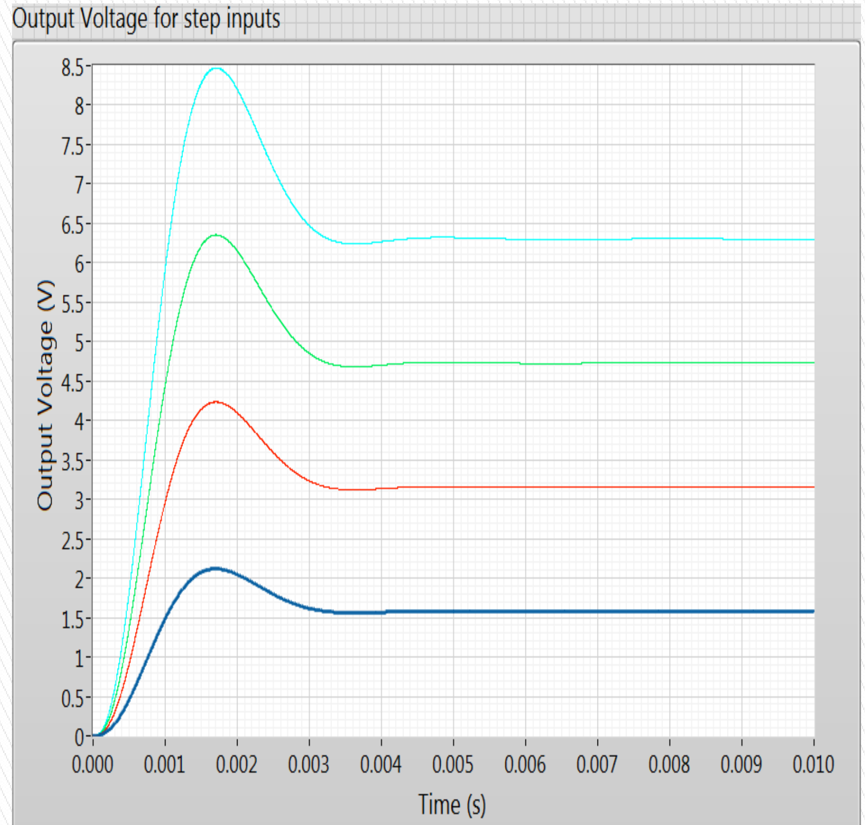
Input acceleration of 1g,2g,3g and 4g.

Output voltage for inputs of 1g,2g,3g and 4g.

Output Voltage for PID tuned using GA

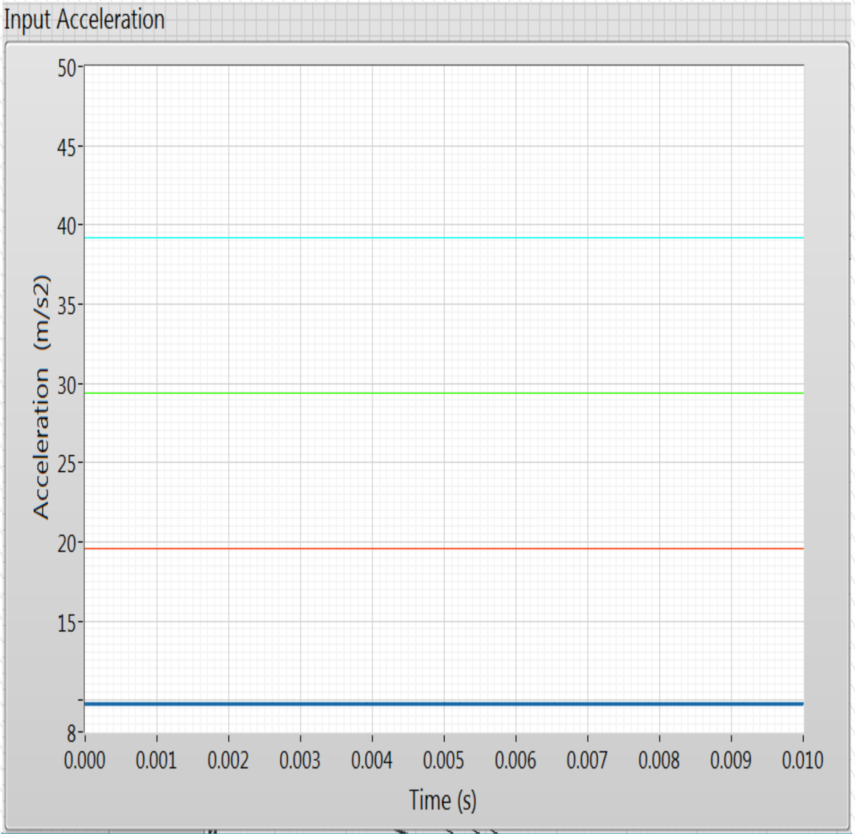


Input acceleration of 1g,2g,3g and 4g.

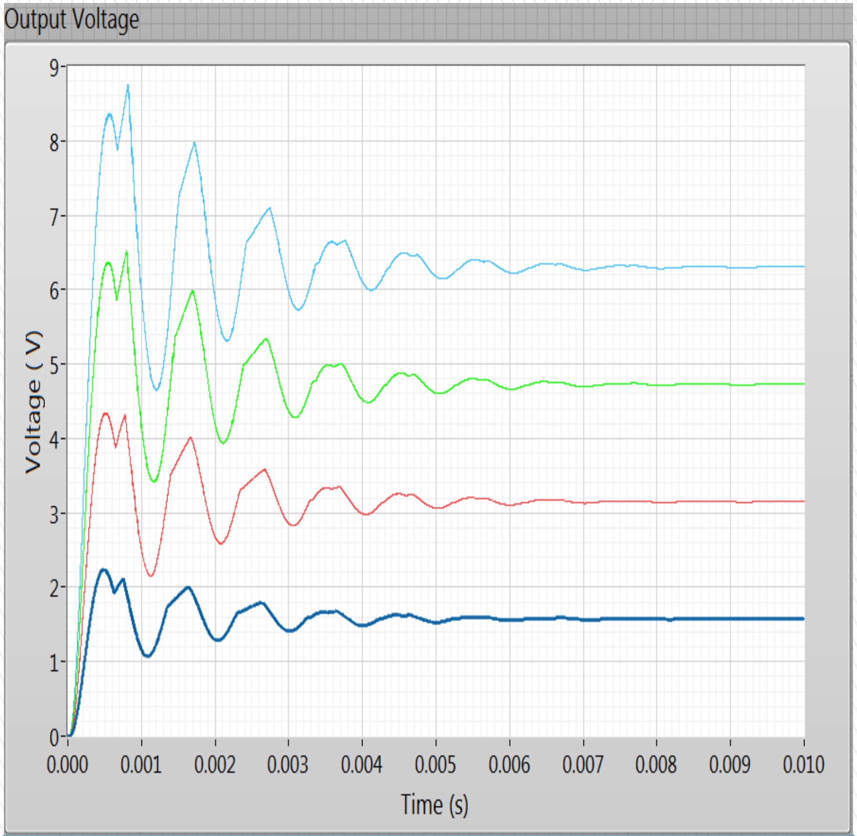


Output voltage for inputs of 1g,2g,3g and 4g.

Output Voltage for Fuzzy PI+ Fuzzy PD tuned using GA



Input acceleration of 1g,2g,3g and 4g.



Output voltage for inputs of 1g,2g,3g and 4g.

Electrostatic Actuator Force

- To generate an electrostatic force apply biasing voltage V_b and feedback voltage on the electrodes.
- Now resulting voltage on electrodes are

$$vs = v1 - Vb + vr$$
$$vi = v2 + Vb + vr$$

Where vs and vi are voltages on upper and lower electrodes

- The electrostatic forces are given as

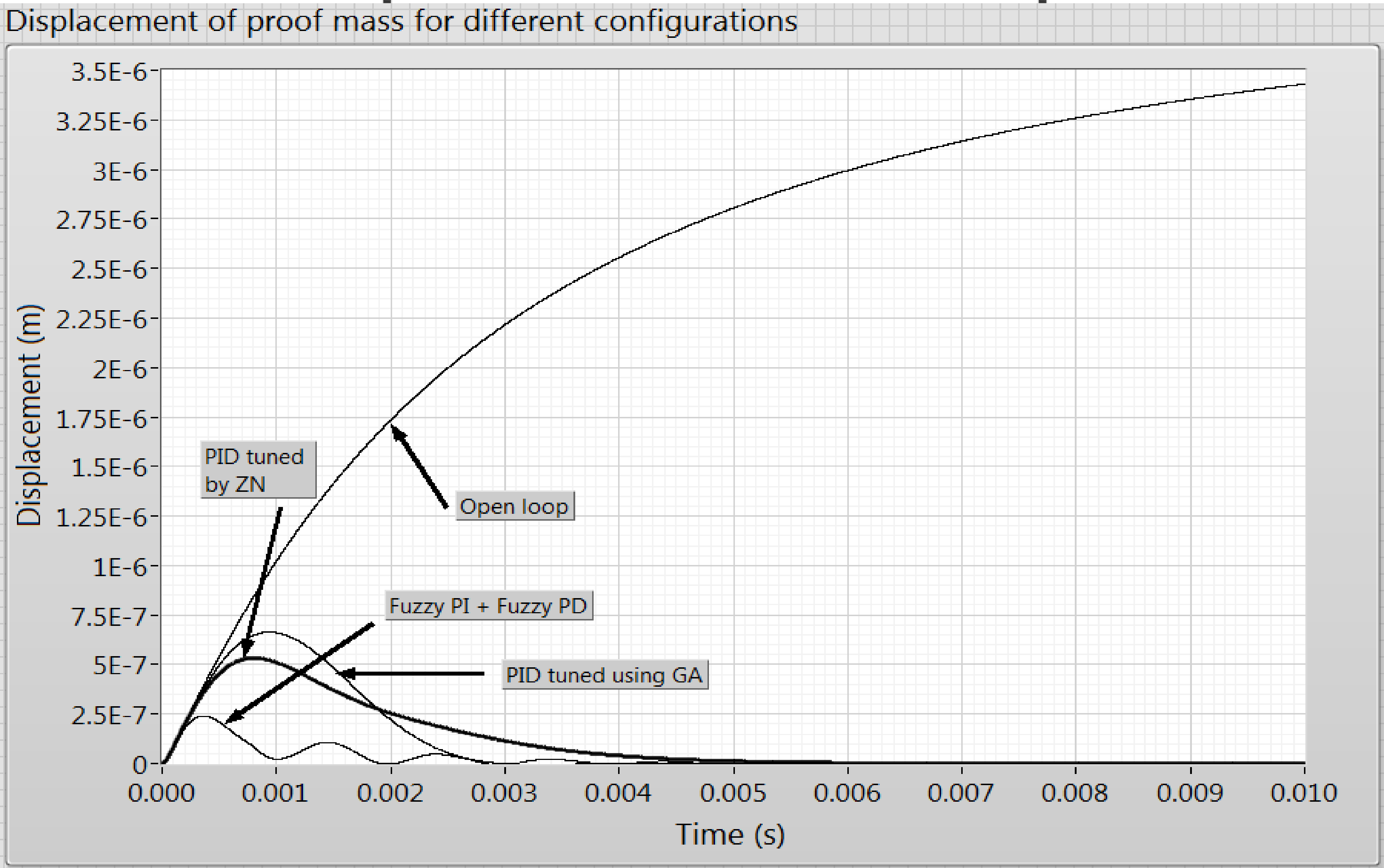
$$Fel1 = \frac{1}{2} e_o A \frac{vs^2}{(do - x)^2} = \frac{1}{2} e_o A \frac{(v1 - Vb + vr)^2}{(do - x)^2}$$
$$Fel2 = \frac{1}{2} e_o A \frac{vi^2}{(do + x)^2} = \frac{1}{2} e_o A \frac{(v2 + Vb + vr)^2}{(do + x)^2}$$

- The resulting electrostatic force is

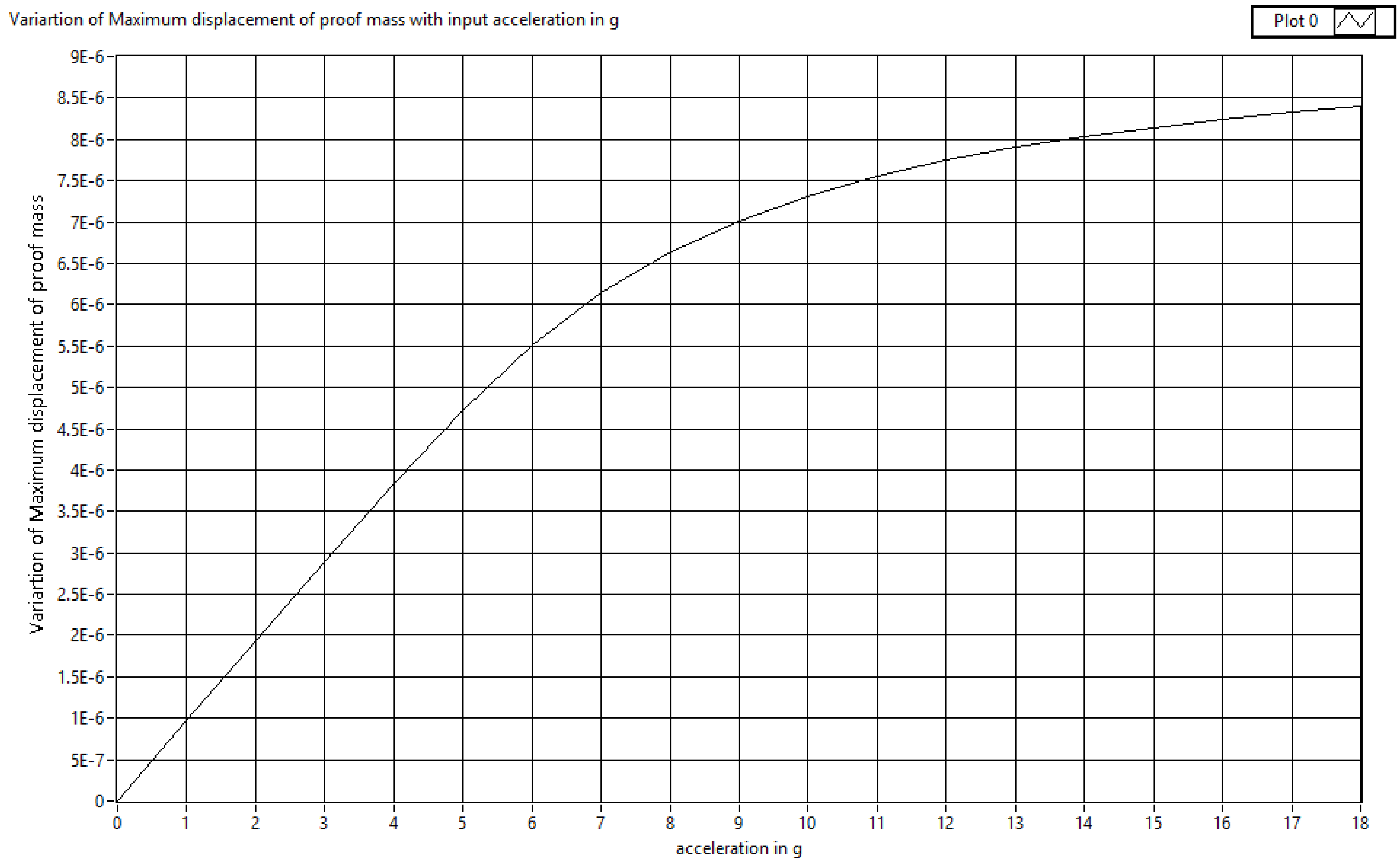
$$Fel = -\frac{2 e_o A V b}{do^2} vr$$

Comparison between Open and Closed loop

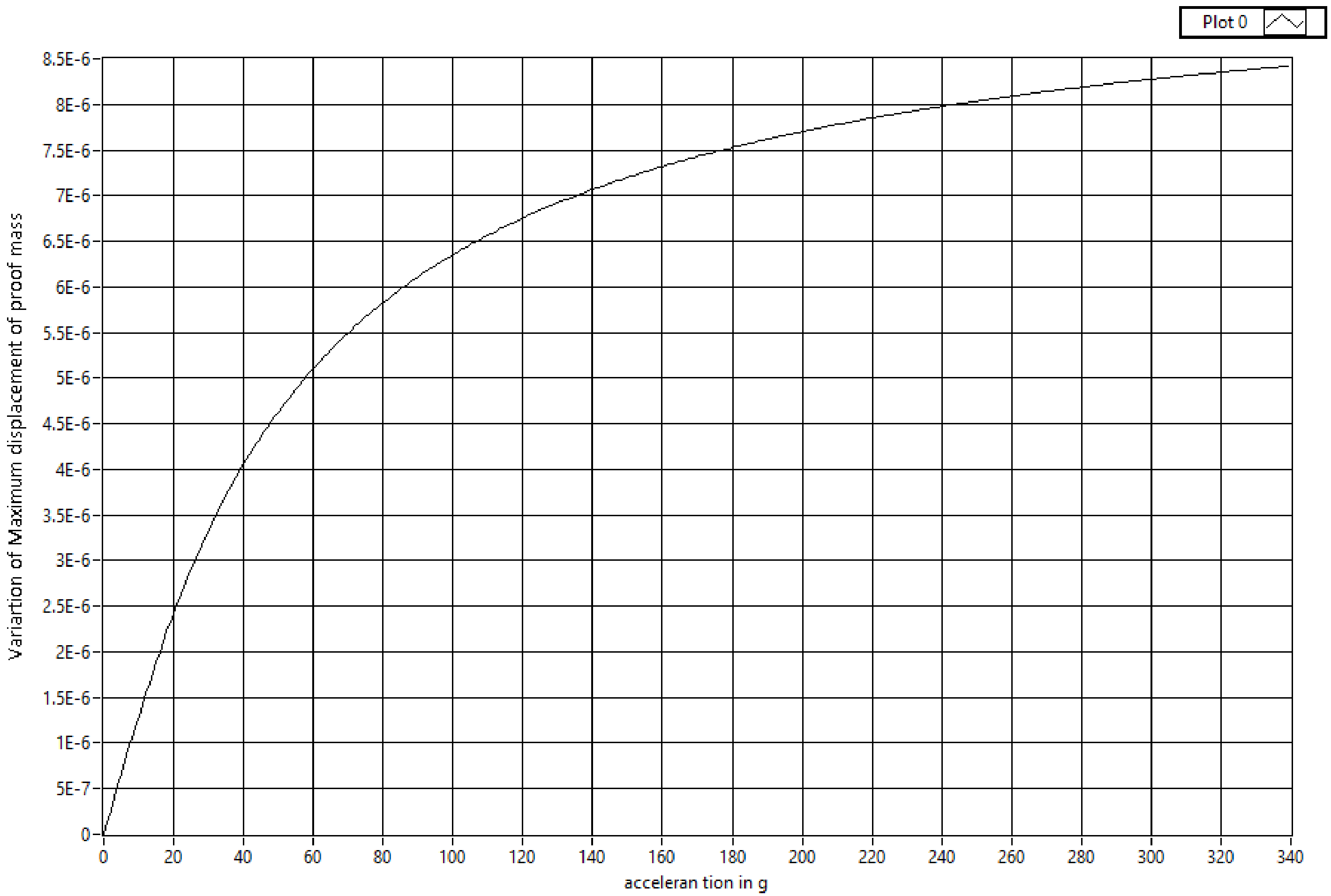
Displacement of proof mass for open and closed loop



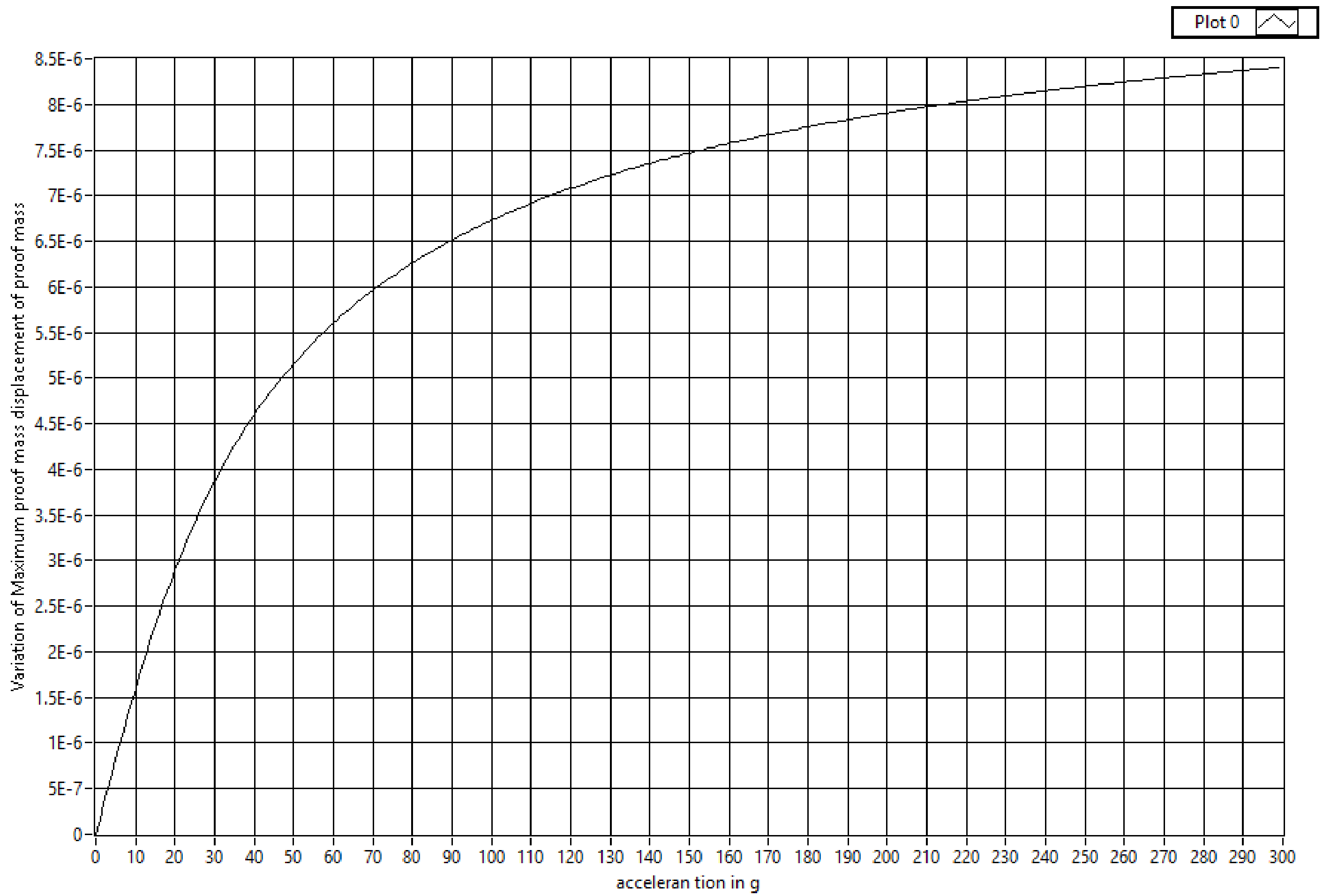
Linear Range for open loop accelerometer



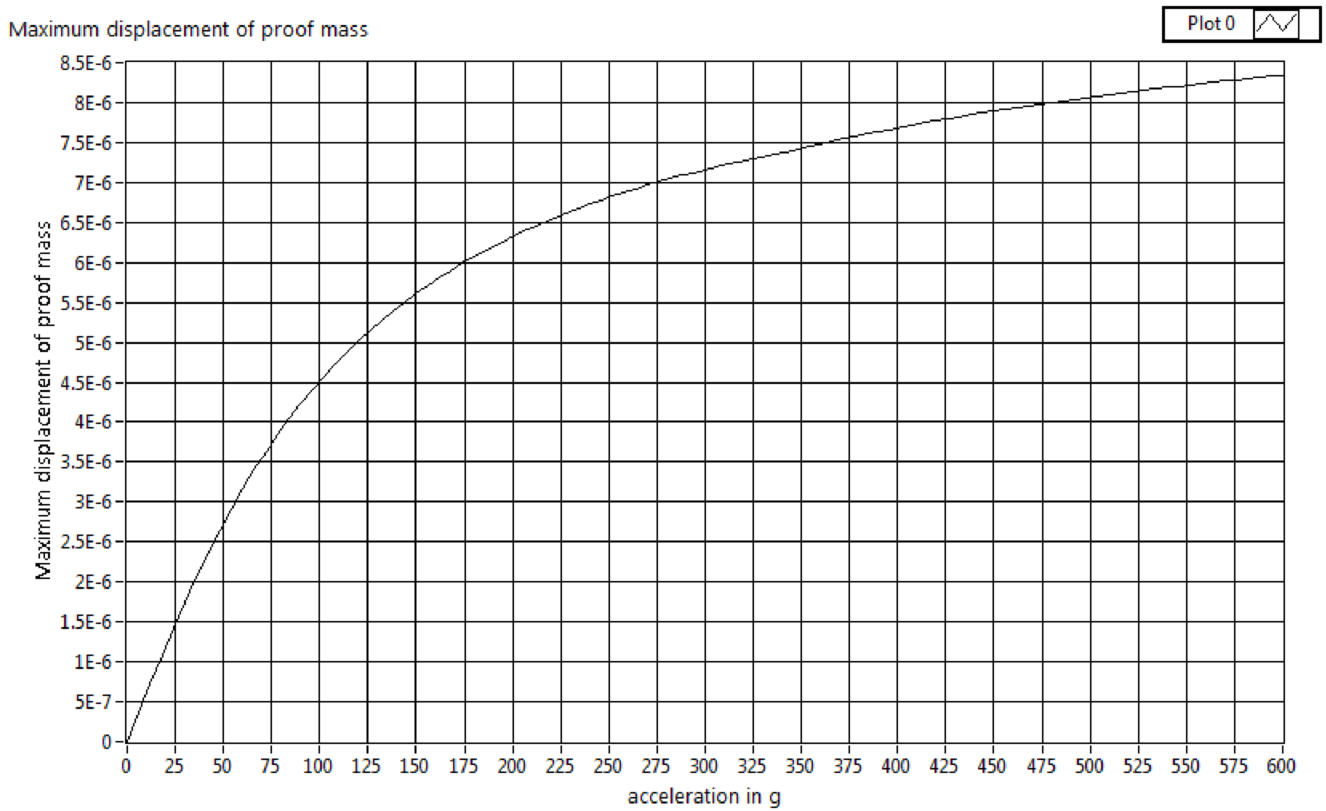
Linear Range for PID tuned using Ziegler-Nichols



Linear Range for PID tuned using GA



Linear Range for Fuzzy PI +Fuzzy PD tuned using GA



Linear Range

Range (Open Loop Accelerometer)	Range (Closed loop Accelerometer with PID controller tuned using Ziegler Nichols)	Range (Closed loop Accelerometer with PID controller tuned using Genetic Algorithms)	Range (Closed loop Accelerometer with Fuzzy PI + Fuzzy PD controller tuned using Genetic Algorithms)
0-4g	0-20g	0-30g	0-50g

Comparison of Maximum displacement of proof Mass

Input acceleration $g = 9.8\ (m/s^2)$	Open Loop Accelerometer (m)	Closed loop Accelerometer with PID controller tuned using Ziegler Nichols (m)	Closed loop Accelerometer with PID controller tuned using Genetic Algorithms (m)	Closed loop Accelerometer with Fuzzy PI + Fuzzy PD controller tuned using Genetic Algorithms (m)
1g	9.65019E-7	1.33E-07	1.67E-07	5.62E-08
2g	1.93008E-6	2.67E-07	3.35E-07	1.142E-7
3g	2.89522E-6	3.99E-07	5E-07	1.751E-7
4g	3.86052E-6	5.32E-07	6.6E-07	2.389E-7

Comparison of ITAE

Input acceleration $g = 9.8(m/s^2)$	Open Loop Accelerometer	Closed loop Accelerometer with PID controller tuned using Ziegler Nichols	Closed loop Accelerometer with PID controller tuned using Genetic Algorithms	Closed loop Accelerometer with Fuzzy PI + Fuzzy PD controller tuned using Genetic Algorithms
1g	4.02947E-11	4.00249E-13	2.82255E-13	8.2868E-14
2g	7.92285E-11	8.00323E-13	5.6471E-13	1.52258E-13
3g	1.15564E-10	1.20005E-12	8.47588E-13	2.20598E-13
4g	1.48391E-10	1.59925E-12	1.13115E-12	2.92764E-13

Comparison of Output Voltage

Input acceleration Here $g = 9.8(m/s^2)$	Open Loop Accelerometer (V)	Closed loop Accelerometer with PID controller tuned using Ziegler Nichols (V)	Closed loop Accelerometer with PID controller tuned using Genetic Algorithms (V)	Closed loop Accelerometer with Fuzzy PI + Fuzzy PD controller tuned using Genetic Algorithms (V)
1g	0.450	1.576	1.576	1.577
2g	0.926	3.151	3.151	3.153
3g	1.457	4.727	4.727	4.728
4g	2.078	6.303	6.303	6.303

Future Work

- Modeling and simulation of tunneling accelerometer which has better sensitivity than capacitive accelerometer

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