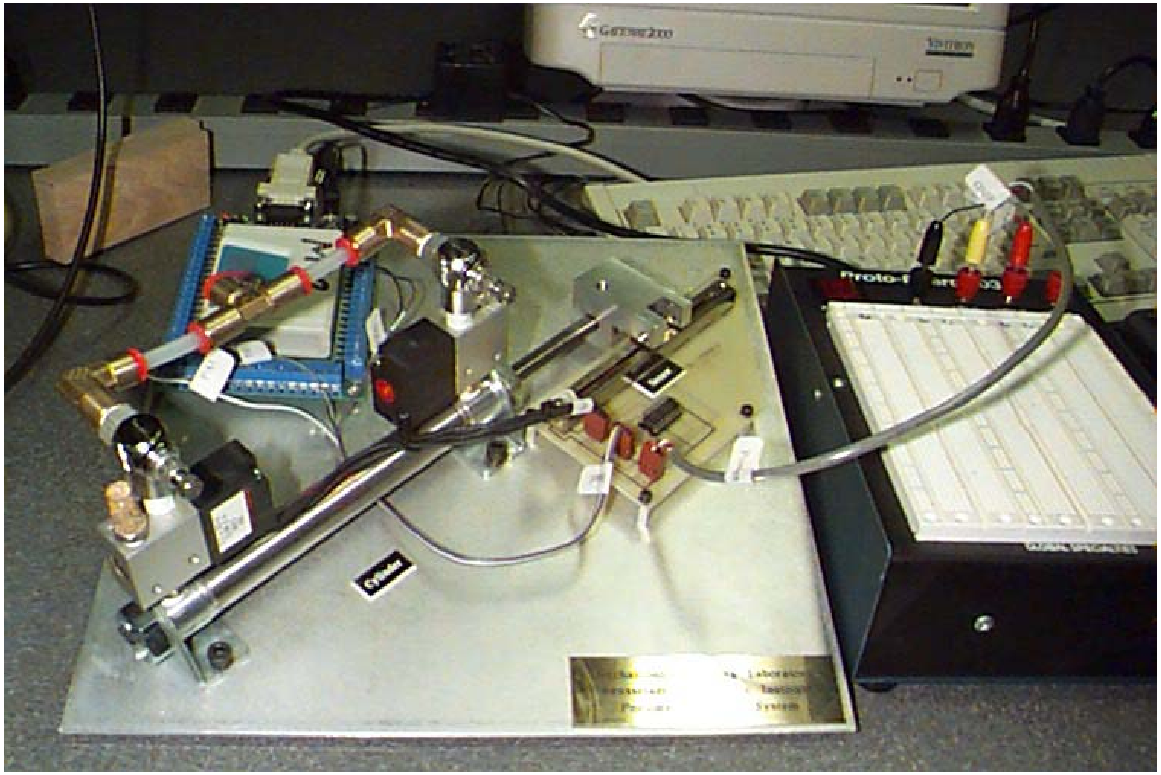
Pneumatic System Closed-Loop, Computer-Controlled Positioning Experiment and Case Study



- 3/4” bore, double-acting, non-rotating air cylinder
- linear potentiometer to measure mass position
- 30 psig air supply
- two flow-control valves
- two 1/8”ported, 3-way, spring-return, two-position solenoid valves
- Darlington switches to energize solenoids
- microcontroller
- on-off, modified on-off, PWM closed-loop control

Pneumatic Actuators for Positioning Applications

- Advantages:
  - Low Cost
  - High Power-to-Weight Ratio
  - Ease of Maintenance
  - Cleanliness
  - Readily Available and Cheap Power Source
- Disadvantages
  - High Friction Forces
  - Deadband due to Stiction
  - Dead Time due to Compressibility of Air

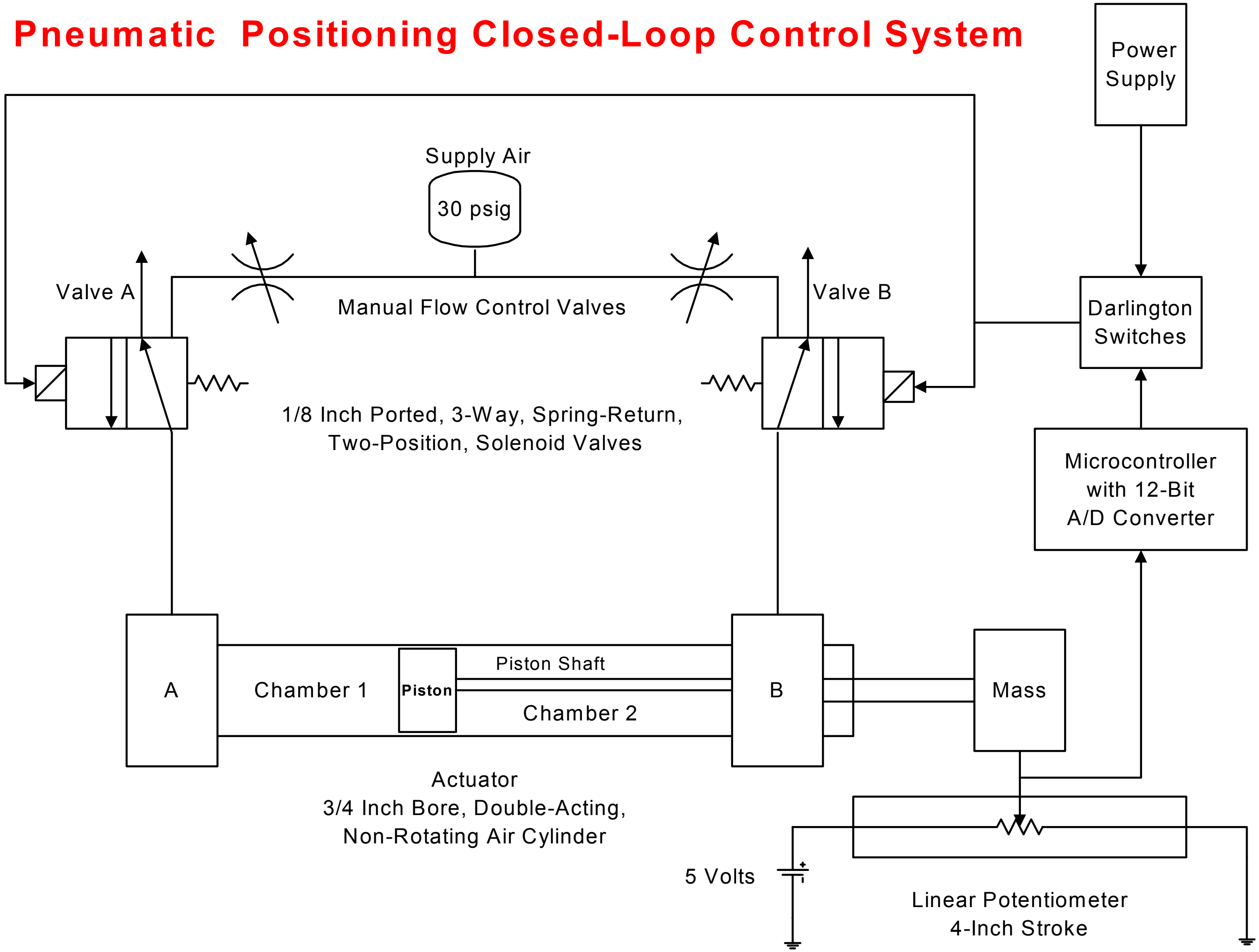
Objective of the Case Study

- Implement inexpensive on/off solenoid valves, rather than servo valves, to develop a fast, accurate, and inexpensive pneumatic actuator system
- Conduct a complete dynamic system investigation of a pneumatic actuator with solenoid-actuated on/off valves
- Design and implement control schemes for closed-loop position control: on/off, modified on/off, and PWM

How Will We Accomplish The Objective ?

- Apply the general procedure for a dynamic system investigation
- Understand the physical system, develop a physical model on which to base analysis and design, and experimentally determine and/or validate model parameter values
- Develop a mathematical model of the system, analyze the system, and compare the results of the analysis to experimental measurements
- Design a feedback control system to meet performance specifications
- Implement the control system and experimentally validate its predicted performance

Schematic of Pneumatic Servomechanism



Properties of the Bimba 3/4-inch Bore Air Cylinder

Specifications	Value
Bore Size (piston diameter)	3/4 inch diameter
Shaft Rod Dimensions	0.28 inches square
Stroke Length	4 inches
Mass of Rod and Piston	0.045 kg (approximate)

Bimba FQPS2K flow-control valves allow for manual adjustment of the orifice flow area. The maximum flow area is a circular port with a 1/8-inch inside diameter. The minimum flow area is zero.

Properties of the Humphrey 310 Series Solenoid Valve

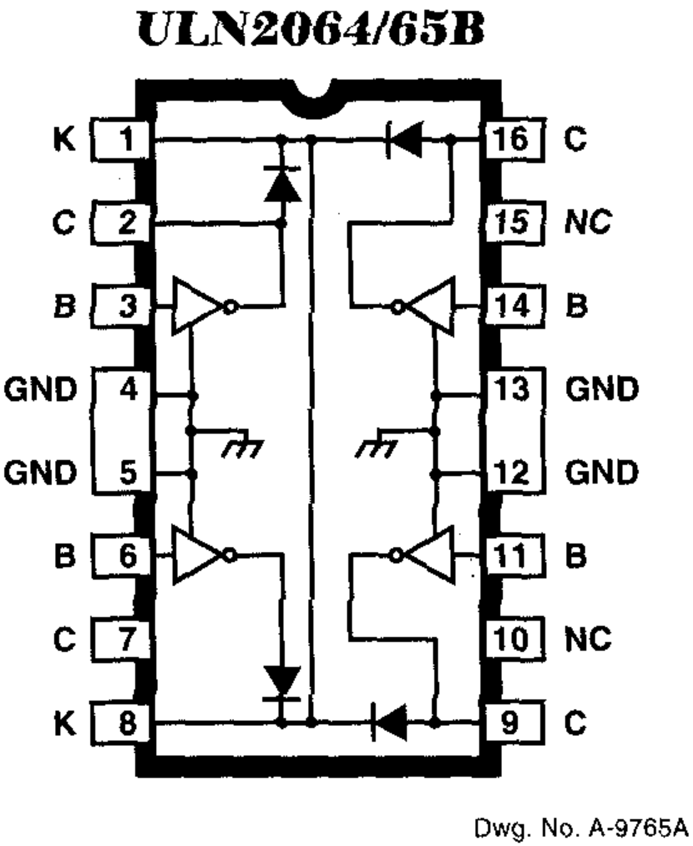
Specifications	Value
Pressure Range	0-125 psig
Power Consumption	4.0 W
Response Time (on/off)	0.011 sec / 0.007 sec
Coil Voltage	12 V DC
Leak Rate (maximum allowed)	4 cc/minute @ 100 psig
Maximum Cycle Rate	45 cycles/second

Properties of the Mouser 312-9401-100K Linear Potentiometer

Specifications	Value
Resistance Tolerance	± 20%
Rated Power	0.5 W
Rated Voltage	500 V
Sliding Life	15,000 cycles
Insulation Resistance	100 MΩ minimum @500 V DC
Withstand Voltage	1 minute @ 500 V AC

Summary of Micro 485 Specifications

Feature	Specification
Microprocessor	Intel 8051 running at 12 MHz
Digital I/O	27 Bi-directional TTL compatible pins
Analog Inputs	4 12-bit 0-5 volt A/D converter channels
Serial Communication	RS-422, RS-232
RAM	128K, battery-backed for retention after power down
ROM	32K, contains on-board Basic and Monitor



The ULN 2064B Quad Darlington Driver for interface between low-level logic and peripheral loads, such as relays, solenoids, and stepper motors

- A high TTL signal (5 volts) at any of the B pins will make a pathway from the corresponding C pin to ground.
- Each channel (there are 4 of them) can handle 1.5 amps.
- The ULN2064B also has internal clamping diodes.

Physical Model Simplifying Assumptions

- All friction is modeled as viscous damping. This combines all frictional effects into one term in the mathematical model.
- The dynamics of the solenoid are approximated. The response of the solenoid is modeled as a 1st-order response.
- The dynamics of the potentiometer are negligible. It is treated as a zero-order system.
- Leakage of the solenoid valves is neglected.
- Fluid is assumed to be a perfect gas.
- The inherent flow-limiting phenomenon known as flow choking is not included in the mathematical model.

- The air-flow model does not account for “reverse flow.” As a result of this assumption, the air pressure in the two chambers of the cylinder is limited to the range of 0 to 30 psig.
- Cylinder is perfectly insulated, i.e, adiabatic conditions.
- The inertia of the air in the chamber is neglected. The only inertia modeled is from the mass of the piston, shaft and aluminum mass.
- The minimum volume in chamber 1, when the cylinder is fully retracted, is equal to $(4-3.5)A_1$ in^3, where A_1 is the area of the piston as seen from chamber 1, i.e., the area of the piston. The minimum volume in chamber 2, when the cylinder is fully extended, is equal to $(0.05)A_2$ in^3, where A_2 is the area of the piston as seen from chamber 2, i.e., the area of the piston minus the area of the piston shaft.

System Parameters

Parameter	Description	Value	Units
m	total mass: piston + piston shaft + mass	0.115	kg
S	stroke length	0.089	m
x	mass position	variable	m
p_1	pressure in chamber 1	variable	N/m^2
p_2	pressure in chamber 2	variable	N/m^2
A_1	chamber 1 area = piston area	2.850E-4	m^2
A_2	chamber 2 area = piston area - shaft area	2.344E-4	m^2
B	viscous damping coefficient	unknown	N-s/m
$\dot{m}_1$	mass flow rate for chamber 1	variable	kg/s
$\dot{m}_2$	mass flow rate for chamber 2	variable	kg/s
$V_{1\text{-min}}$	minimum volume for chamber 1	3.620E-6	m^3
$V_{2\text{-min}}$	minimum volume for chamber 2	2.977E-7	m^3
T	air temperature	294	°K
A_{flow1}	flow control valve 1 maximum orifice area	7.917E-6	m^2
A_{flow2}	flow control valve 2 maximum orifice area	7.917E-6	m^2
p_s	supply air pressure	2.07E5	N/m^2
p_e	exhaust air pressure	0	N/m^2
ρ	density of air	1.3	kg/m^3
τ_{dt1}	time delay for solenoid valve 1	0.011	s
τ_{dt2}	time delay for solenoid valve 2	0.011	s
γ	specific heat ratio	1.4	-
R	ideal gas constant	287	J/kg-°K

Mathematical Modeling

- Define system, system boundary, system inputs and output
- Define through and across variables
- Write physical relations for each element
- Write system relations of equilibrium and/or compatibility
- Combine system relations and physical relations to generate the mathematical model for the system

Mathematical Model

Three major considerations are determination of:

- mass flow rate through each valve
- pressure, volume, and temperature of the air in the cylinder
- dynamics of the load

Flow through a Sharp-Edged Orifice:

$$\boxed{\begin{aligned}&\dot{m} = CA\sqrt{2\rho\left(p_1 - p_2\right)}\\&C \approx 0.5\end{aligned}}$$

Newton's 2nd Law:

$$\boxed{m\ddot{x} = p_1A_1 - p_2A_2 - F_f}$$

Conservation of Energy:

$$\dot{Q}+\dot{W}=\frac{\partial}{\partial t}\int_{cv} e\rho dV+\int_{cs}\left(u+\frac{p}{\rho}+\frac{v^2}{2}+gz\right)\rho\vec{v}\bullet d\vec{A}$$

$$\dot{Q}+C_p\left(\dot{m}_{in}T_{in}-\dot{m}_{out}T_{cv}\right)+\dot{W}=\frac{d}{dt}U_{cv}$$

$$U_{cv}=m_{cv}C_vT_{cv}=\rho_{cv}V_{cv}C_vT_{cv}=\frac{C_v}{R}p_{cv}V_{cv} \qquad \text{since } p=\rho RT$$

$$\dot{U}_{cv}=\frac{1}{\gamma-1}\left[p_{cv}\dot{V}_{cv}+V_{cv}\dot{p}_{cv}\right] \qquad \text{since } C_v\approx\frac{R}{\gamma-1}$$

$$\dot{W} = p_{cv}\dot{V}_{cv} \quad \text{and} \quad C_p \approx \frac{\gamma R}{\gamma - 1}$$

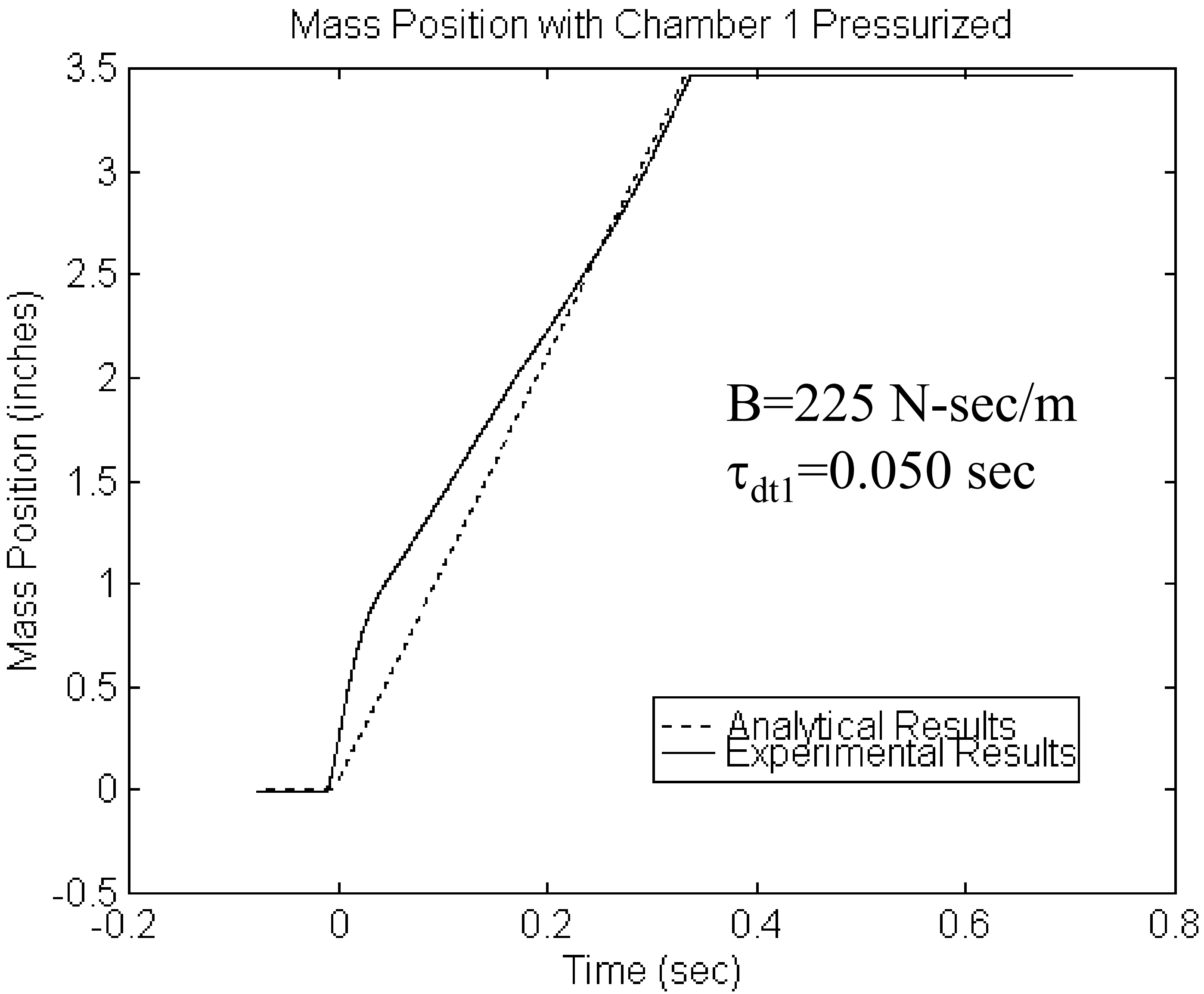
Therefore

$$q_{net} + \frac{\gamma R}{\gamma - 1}\left(\dot{m}_{in}T_{in} - \dot{m}_{out}T_{cv}\right) = \frac{1}{\gamma - 1}\left[p_{cv}\dot{V}_{cv} + \dot{p}_{cv}V_{cv}\right] + p_{cv}\dot{V}_{cv}$$

For $q_{net} = 0$ and $\dot{m}_{out} = 0$

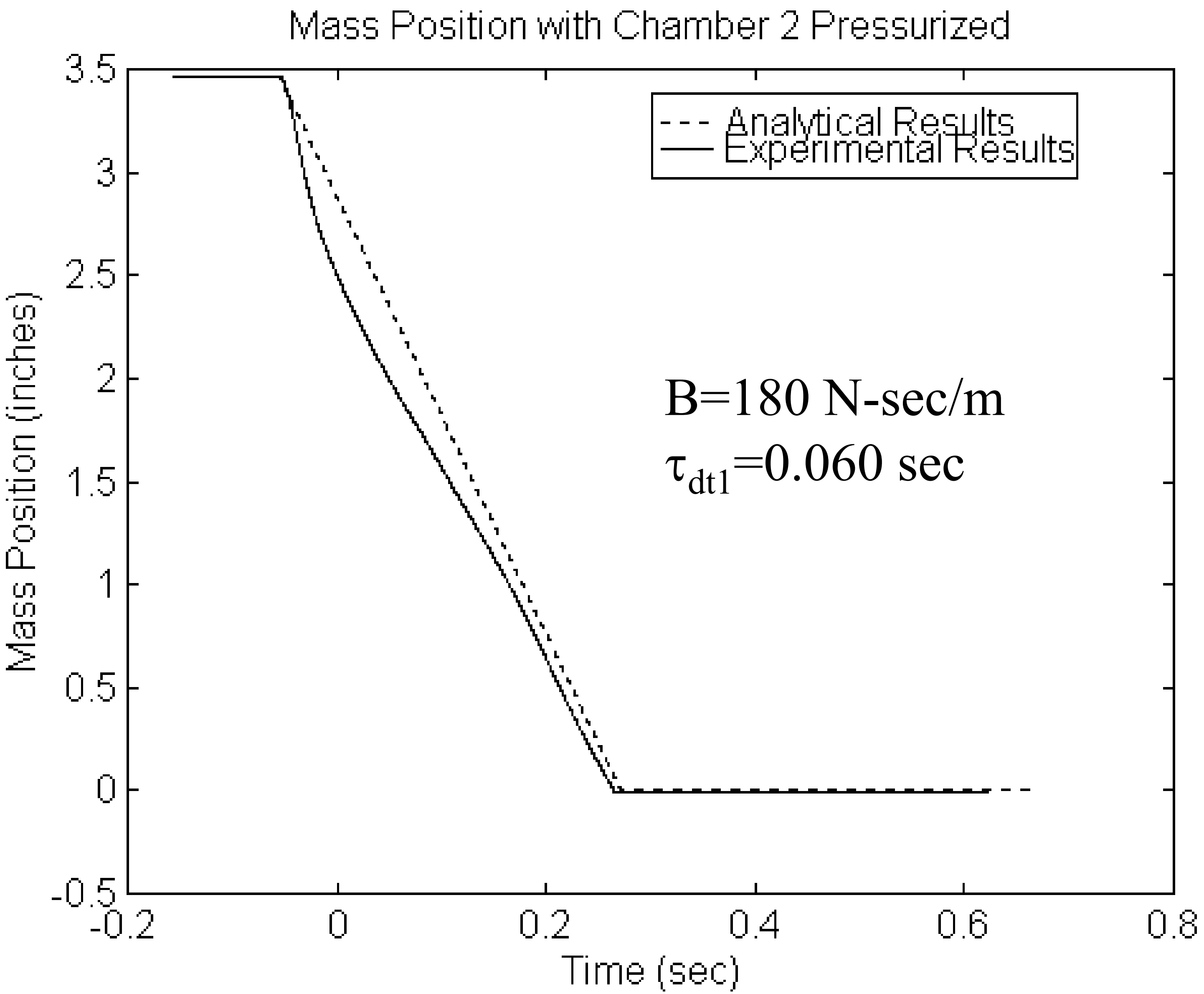
$$\dot{m}_{in} = \frac{1}{RT_{in}}\left[p_{cv}\dot{V}_{cv} + \frac{1}{\gamma}V_{cv}\dot{p}_{cv}\right]$$

$$\boxed{\begin{aligned} \dot{m}_1 &= A_1\dot{x}\frac{p_1}{RT} + \frac{V_{1-\min} + A_1 x}{\gamma RT}\dot{p}_1 \\ \dot{m}_2 &= -A_2\dot{x}\frac{p_2}{RT} + \frac{V_{2-\min} + A_2(S - x)}{\gamma RT}\dot{p}_2 \end{aligned}}$$



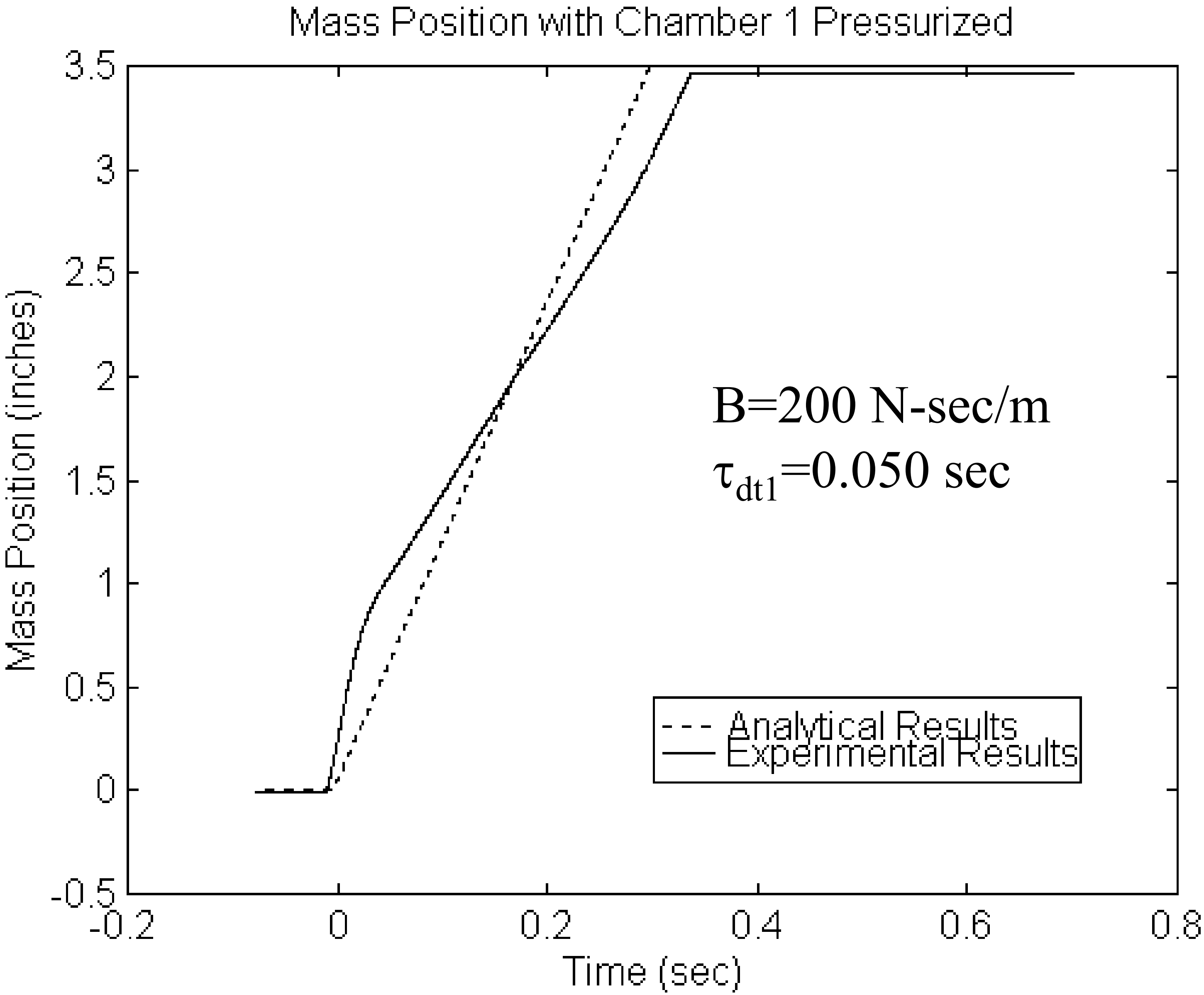
B=225 N-sec/m

τ_{dt1}=0.050 sec



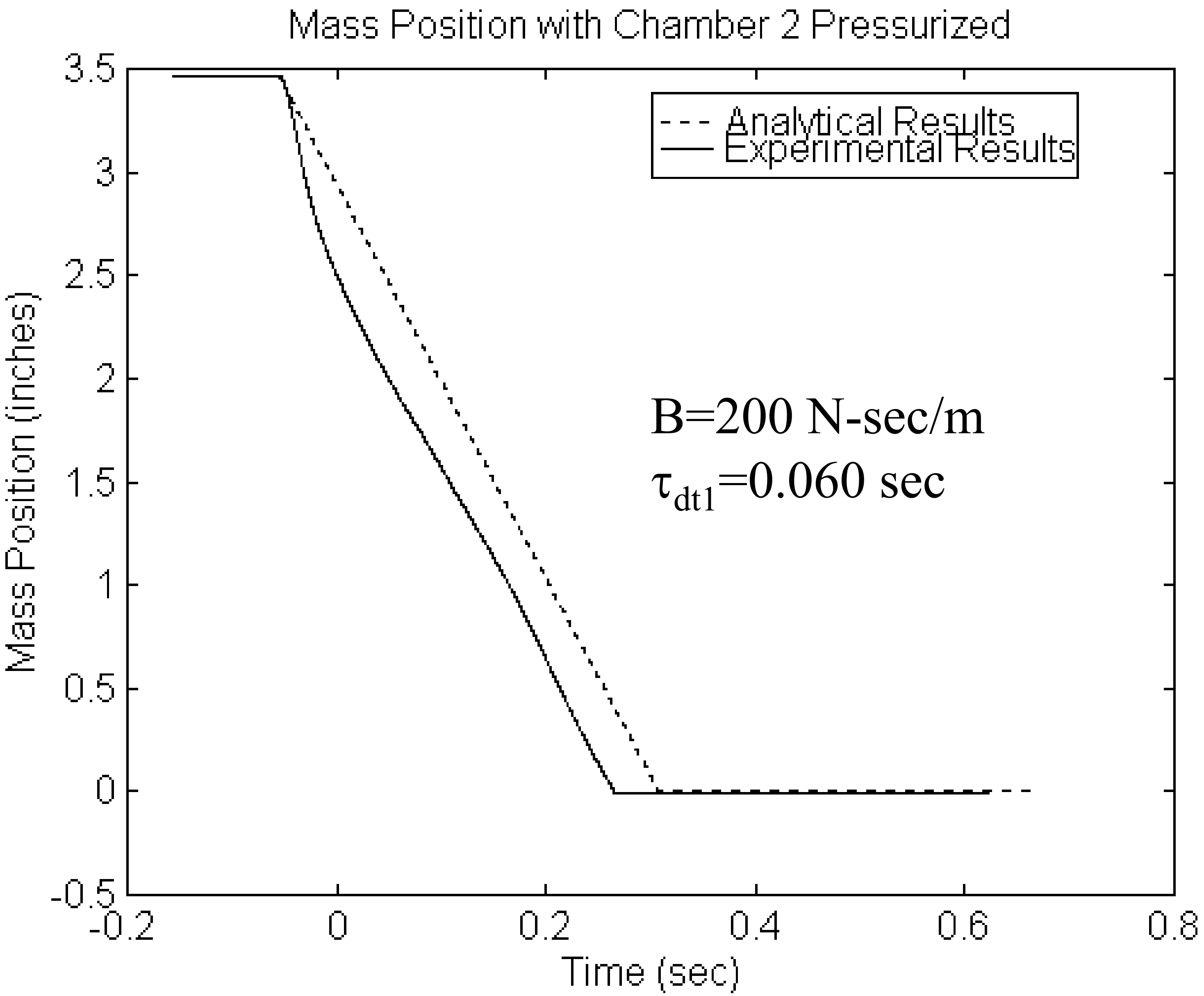
B=180 N-sec/m

τ_{dt1}=0.060 sec



B=200 N-sec/m

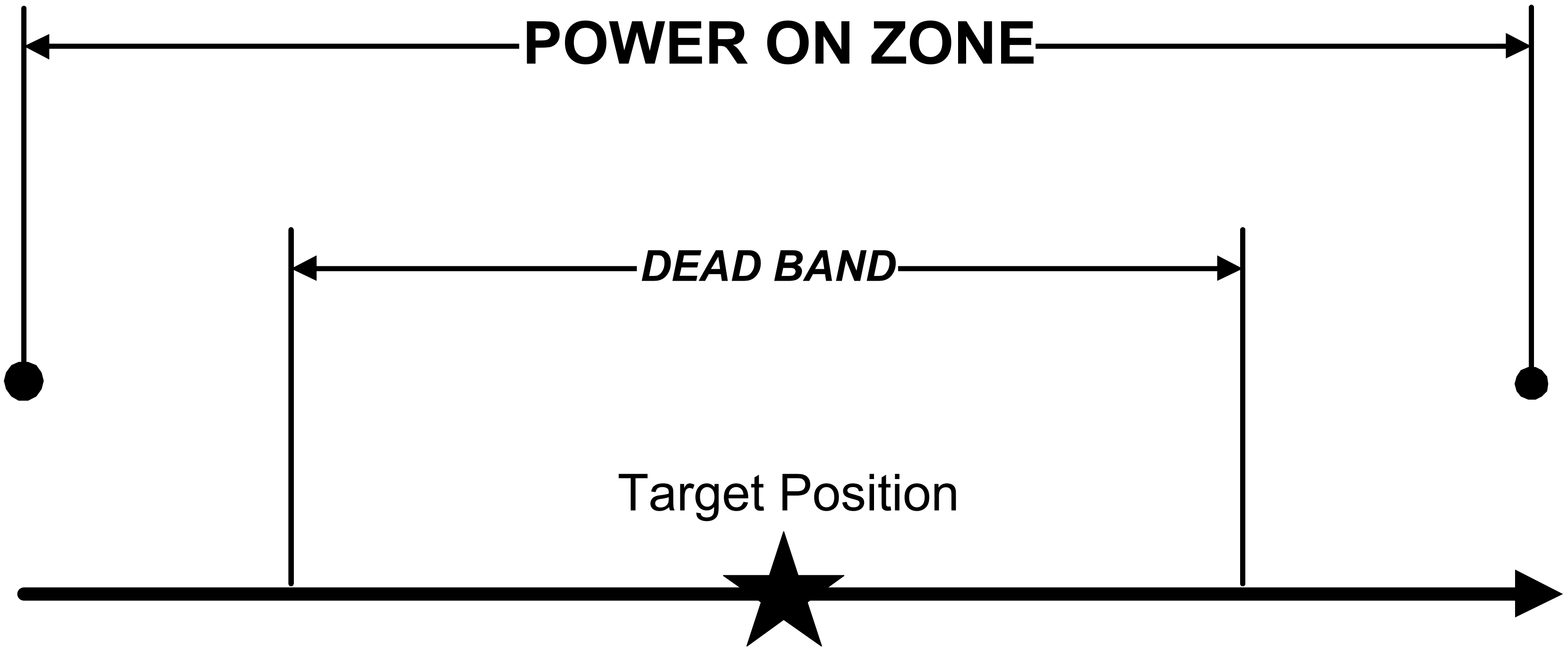
τ_{dt1}=0.050 sec

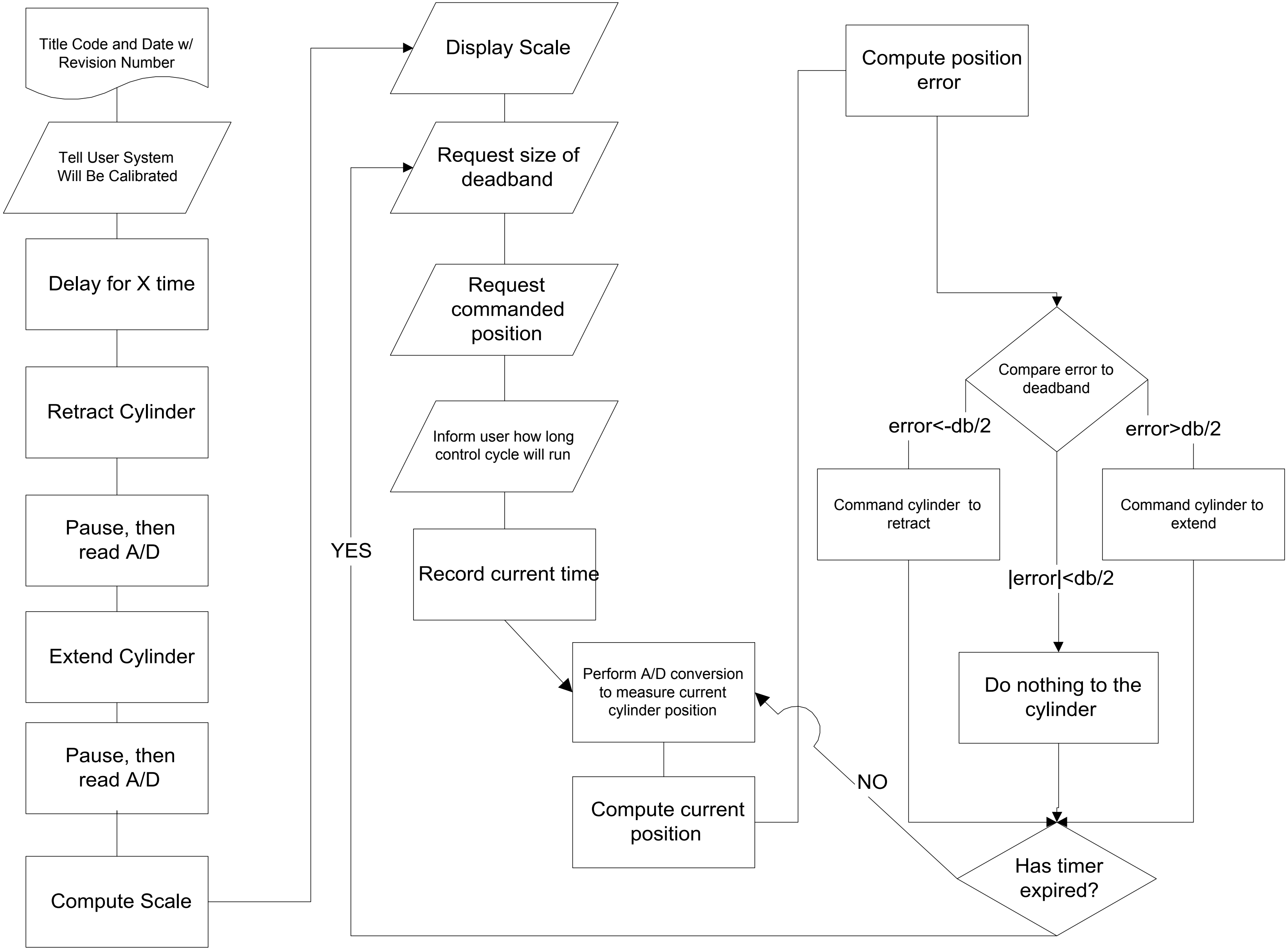


B=200 N-sec/m

τ_{dt1}=0.060 sec

Control System Design:
On-Off Control





Title Code and Date w/ Revision Number

Tell User System Will Be Calibrated

Delay for X time

Retract Cylinder

Pause, then read A/D

Extend Cylinder

Pause, then read A/D

Compute Scale

Display Scale

Request size of deadband

Request commanded position

Inform user how long control cycle will run

Record current time

Perform A/D conversion to measure current cylinder position

Compute current position

Compute position error

Compare error to deadband

error<-db/2

Command cylinder to retract

|error|<db/2

Do nothing to the cylinder

error>db/2

Command cylinder to extend

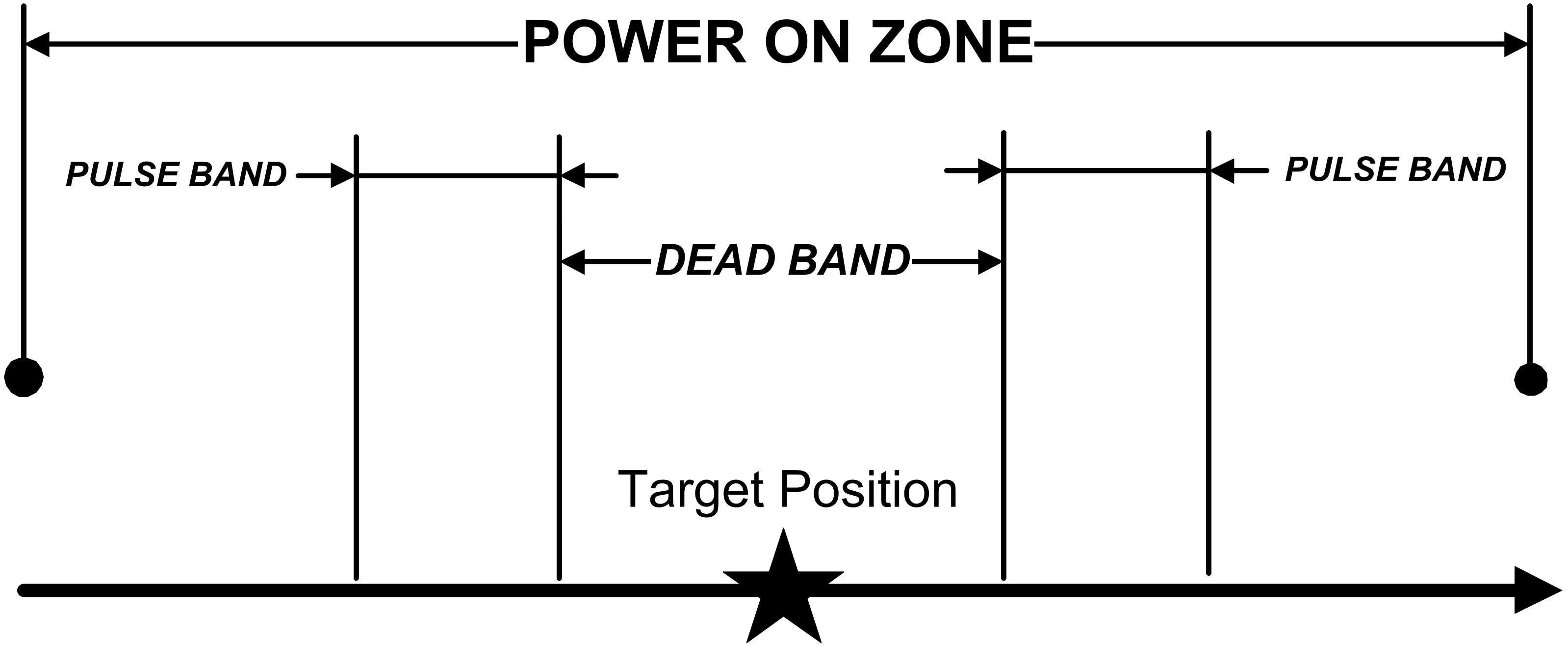
Has timer expired?

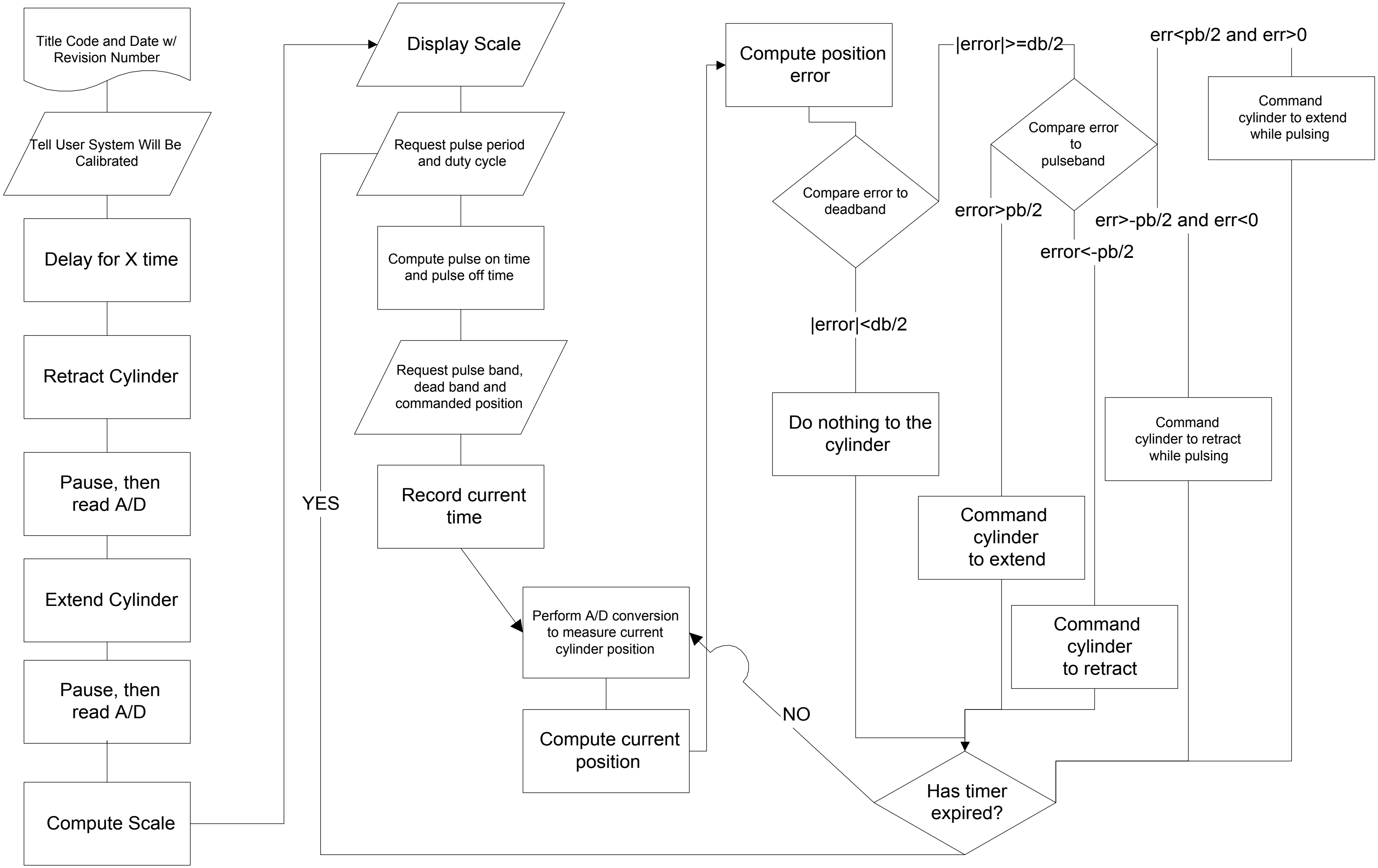
YES

NO

On-Off Control

Control System Design: Modified On-Off Control





Title Code and Date w/ Revision Number

Tell User System Will Be Calibrated

Delay for X time

Retract Cylinder

Pause, then read A/D

Extend Cylinder

Pause, then read A/D

Compute Scale

Display Scale

Request pulse period and duty cycle

Compute pulse on time and pulse off time

Request pulse band, dead band and commanded position

Record current time

Perform A/D conversion to measure current cylinder position

Compute current position

Compute position error

Compare error to deadband

|error|<db/2

Do nothing to the cylinder

|error|>=db/2

Compare error to pulseband

error>pb/2

Command cylinder to extend

error<-pb/2

Command cylinder to retract

err<pb/2 and err>0

Command cylinder to extend while pulsing

err>-pb/2 and err<0

Command cylinder to retract while pulsing

Has timer expired?

YES

NO

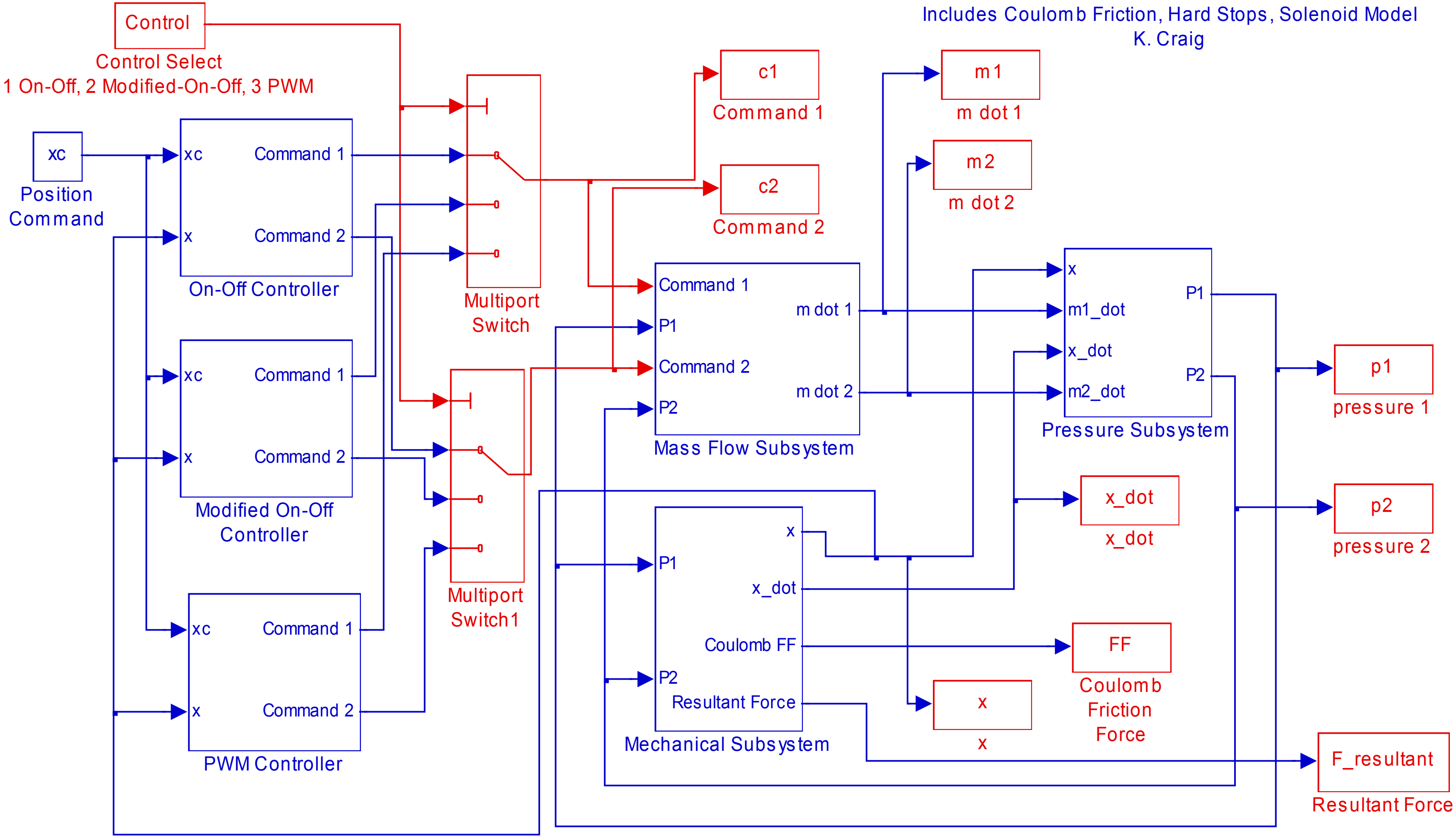
Modified On-Off Control

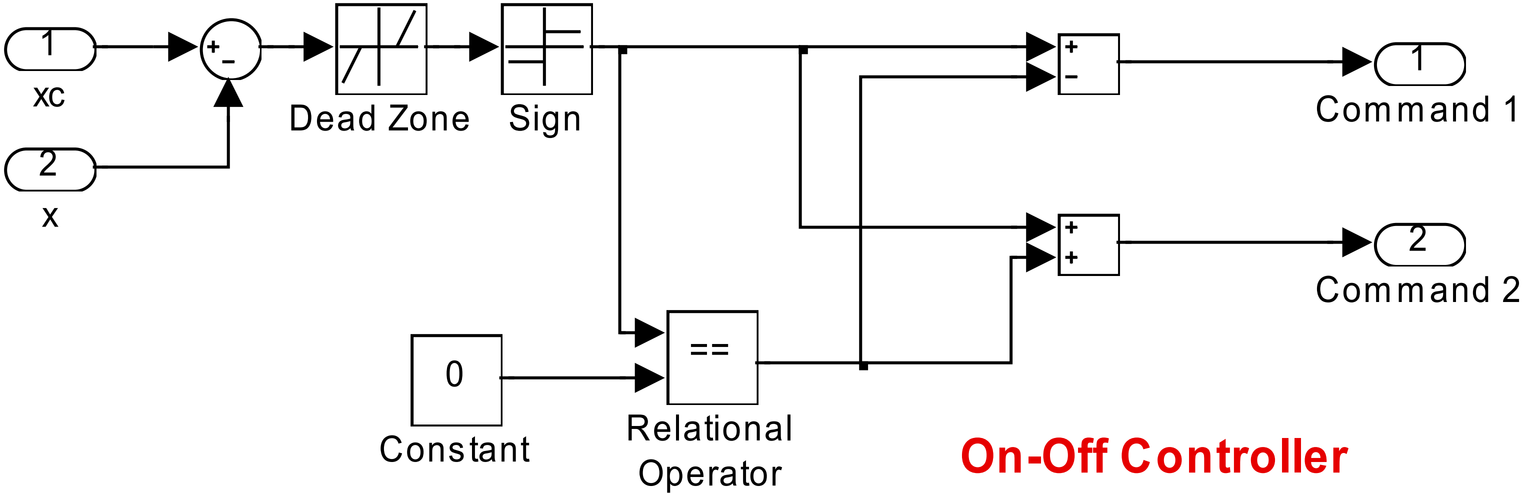
Control Logic for the On /Off Control Scheme

Position Error	**Dead Zone Output**	**Switch One**	**Switch Two**
|Err|<(Dead Band/2)	0	-1	1
Err>(Dead Band/2)	1	1	1
Err<-(Dead Band/2)	-1	-1	-1

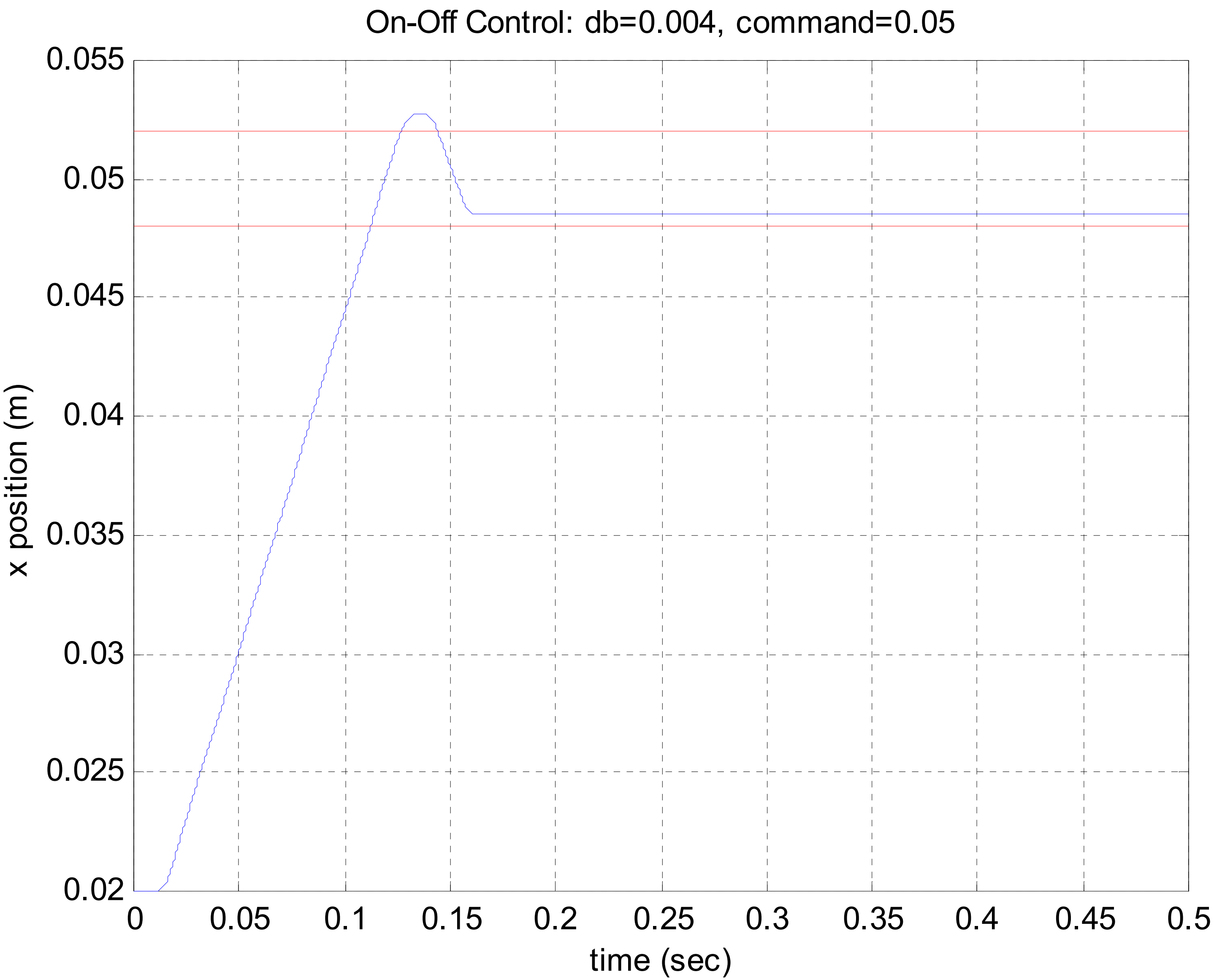
Pneumatic System Closed-Loop Position Control: On-Off, Modified On-Off, PWM

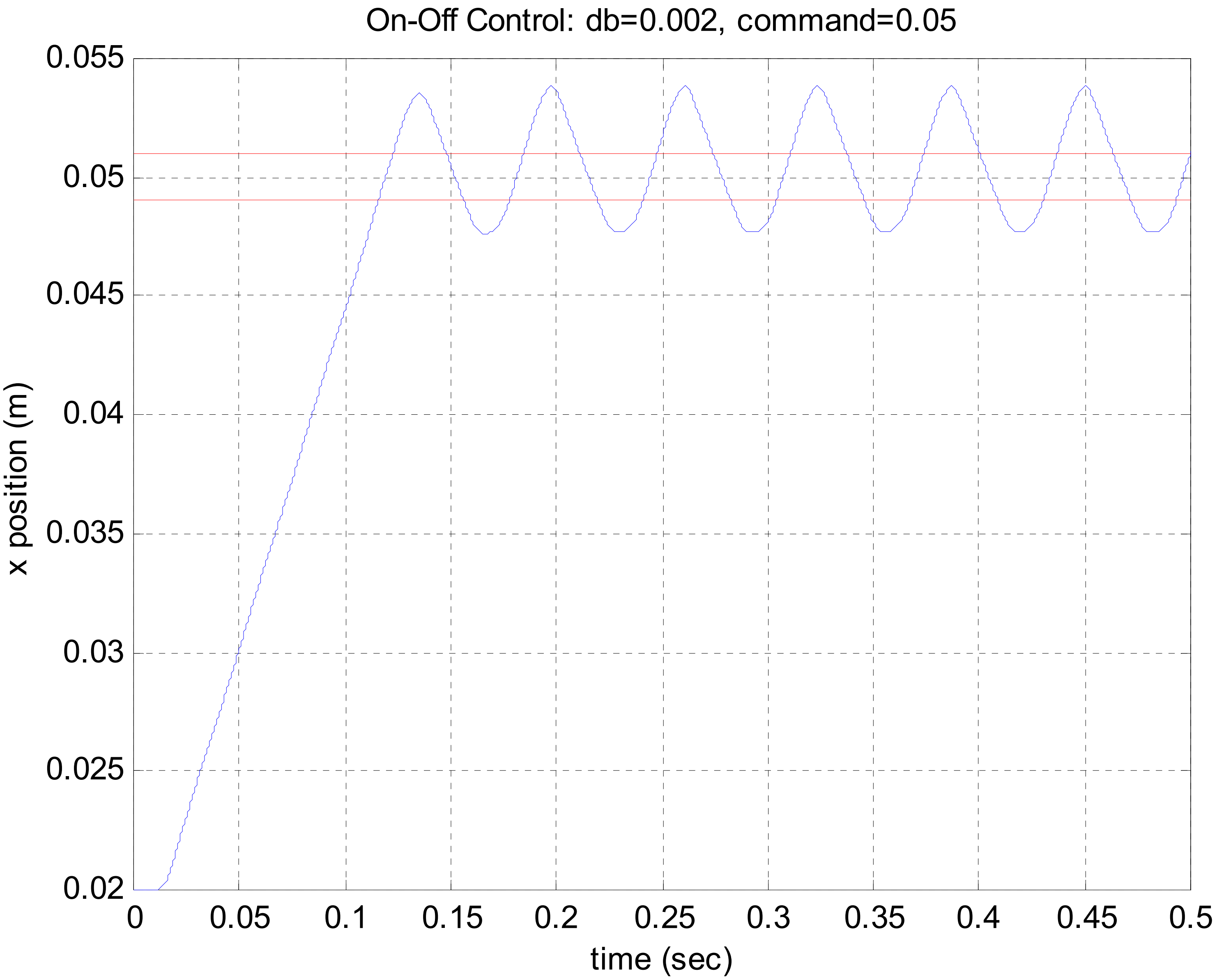
Includes Coulomb Friction, Hard Stops, Solenoid Model
K. Craig



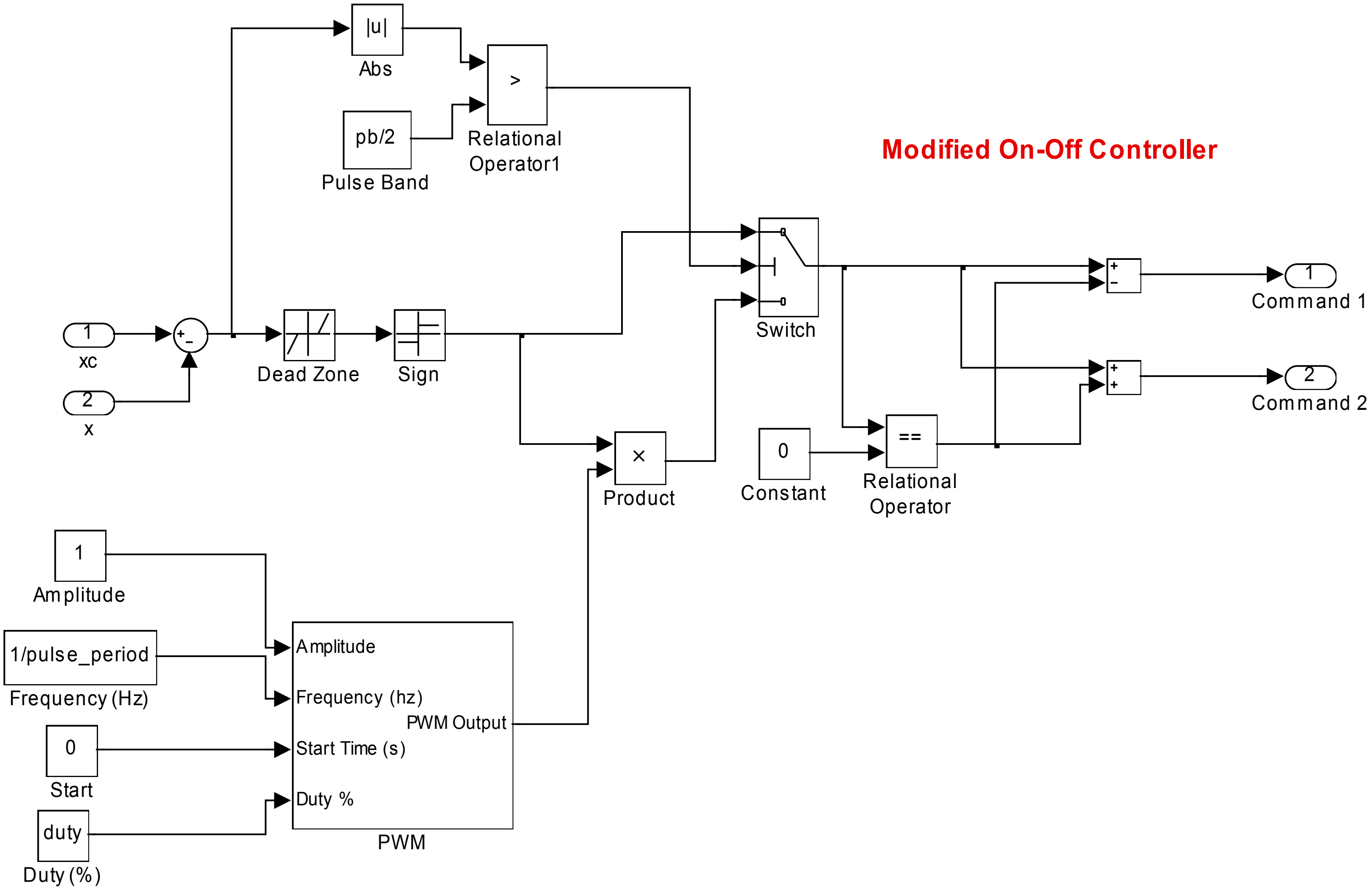


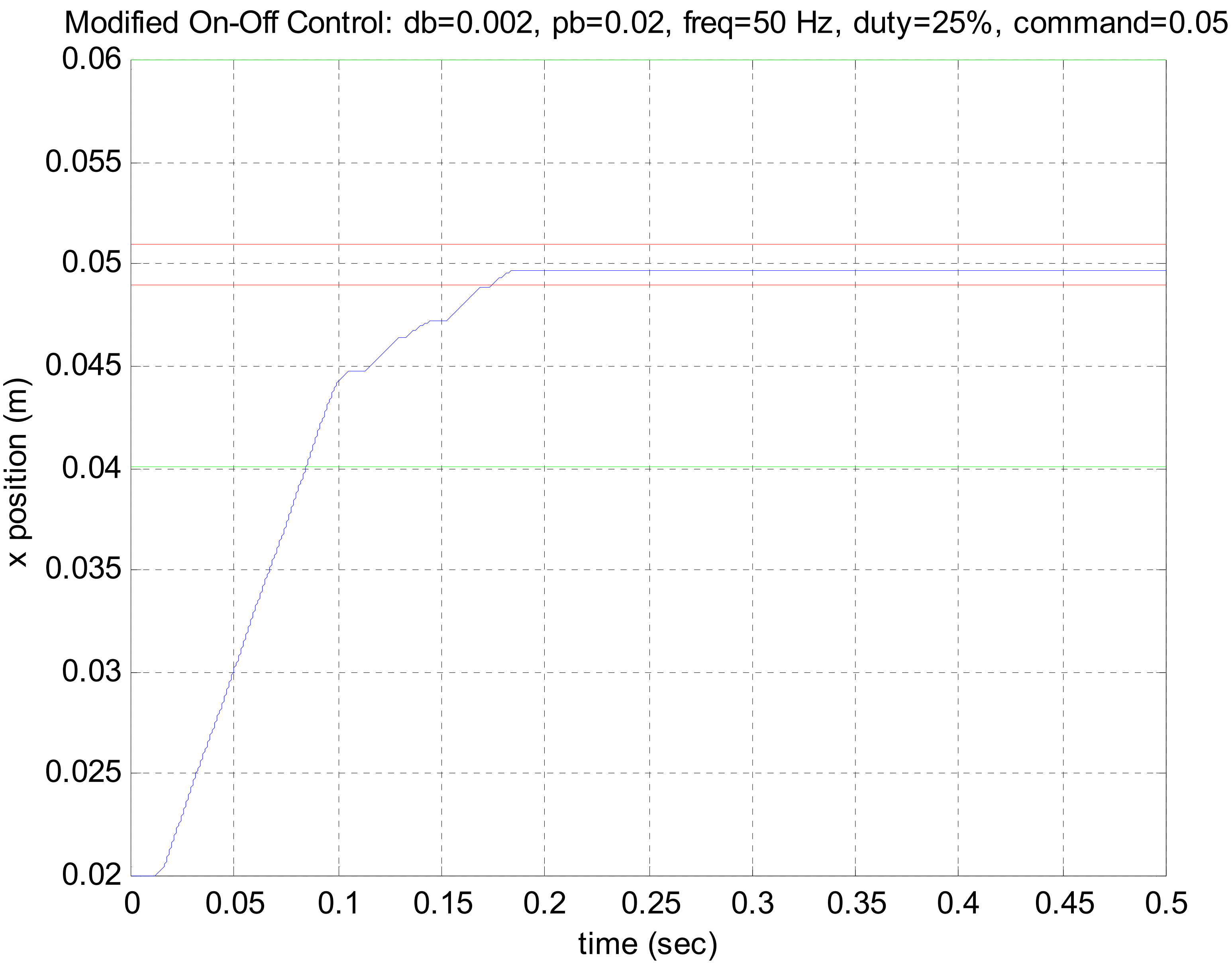
On-Off Controller

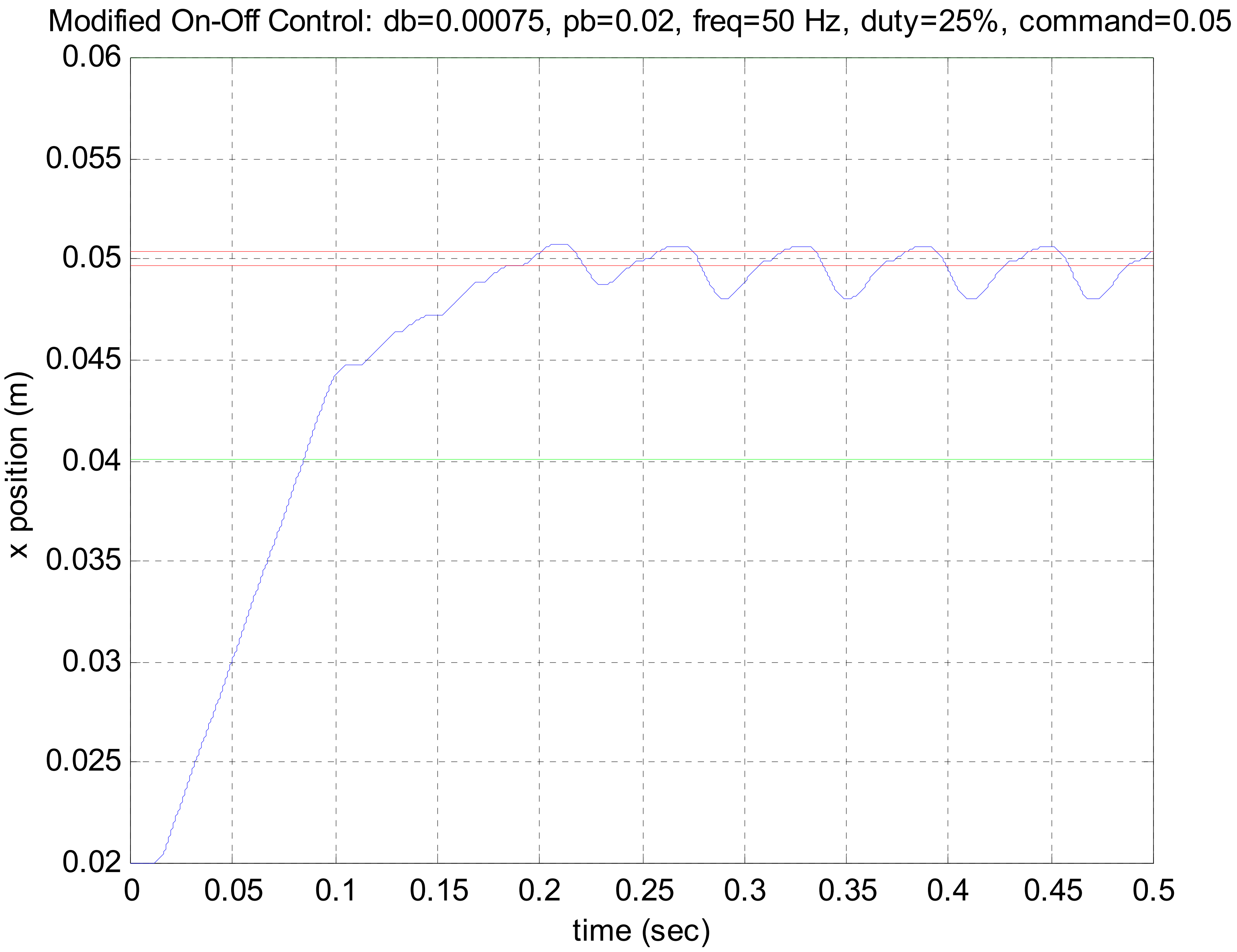

On-Off Control: db=0.004, command=0.05
x position (m)
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
time (sec)


On-Off Control: db=0.002, command=0.05
x position (m)
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
time (sec)

Modified On-Off Controller

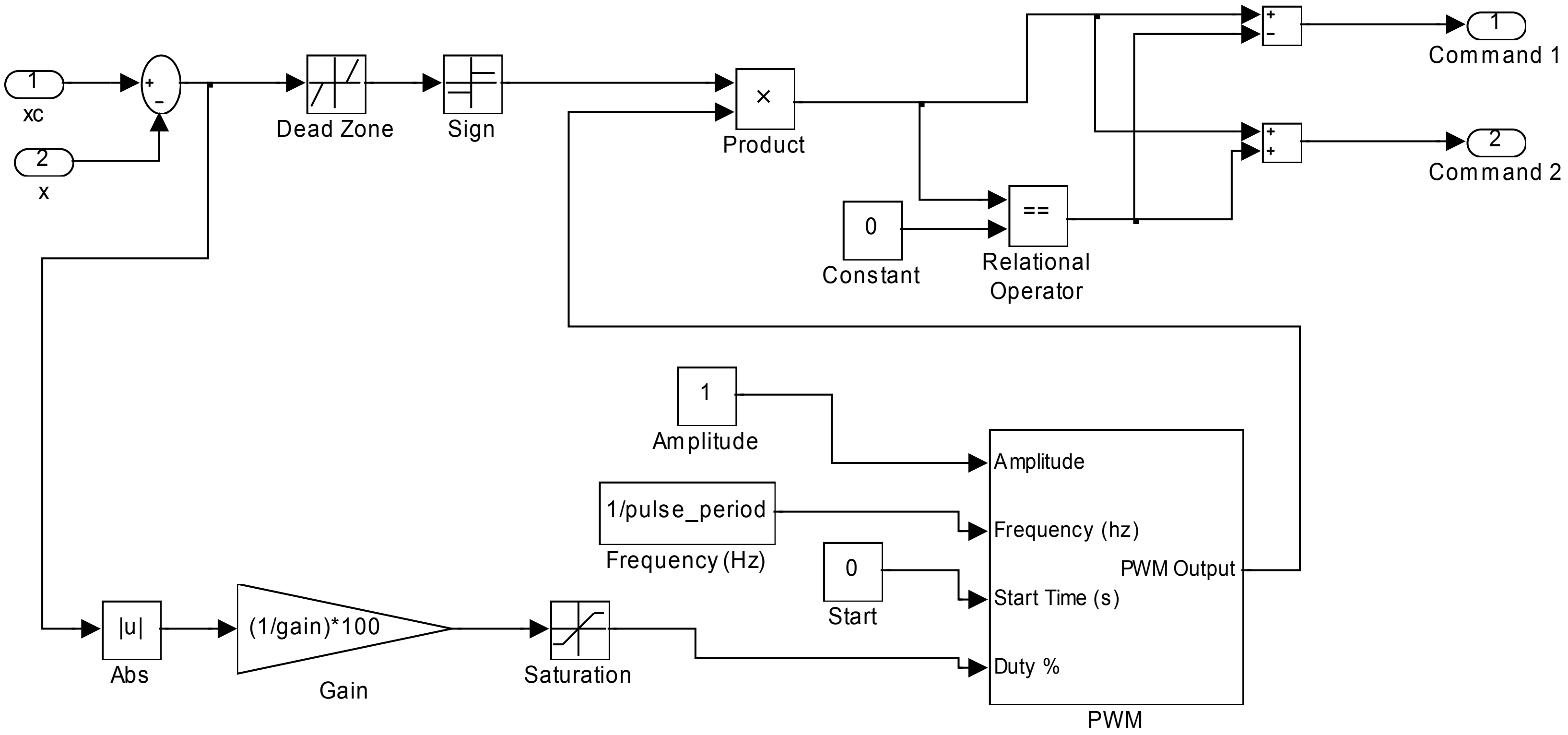


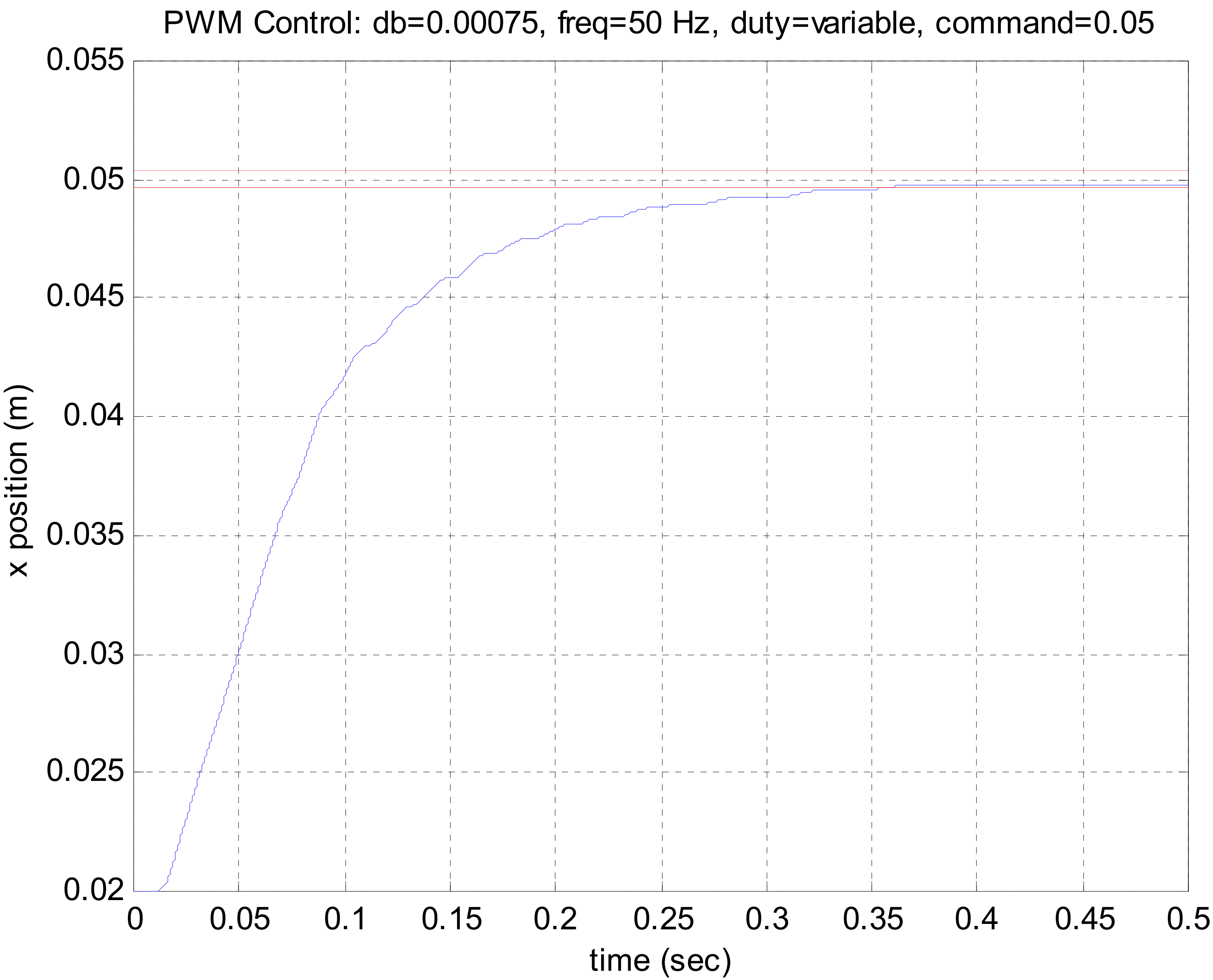

Modified On-Off Control: db=0.002, pb=0.02, freq=50 Hz, duty=25%, command=0.05
0.06
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
x position (m)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
time (sec)

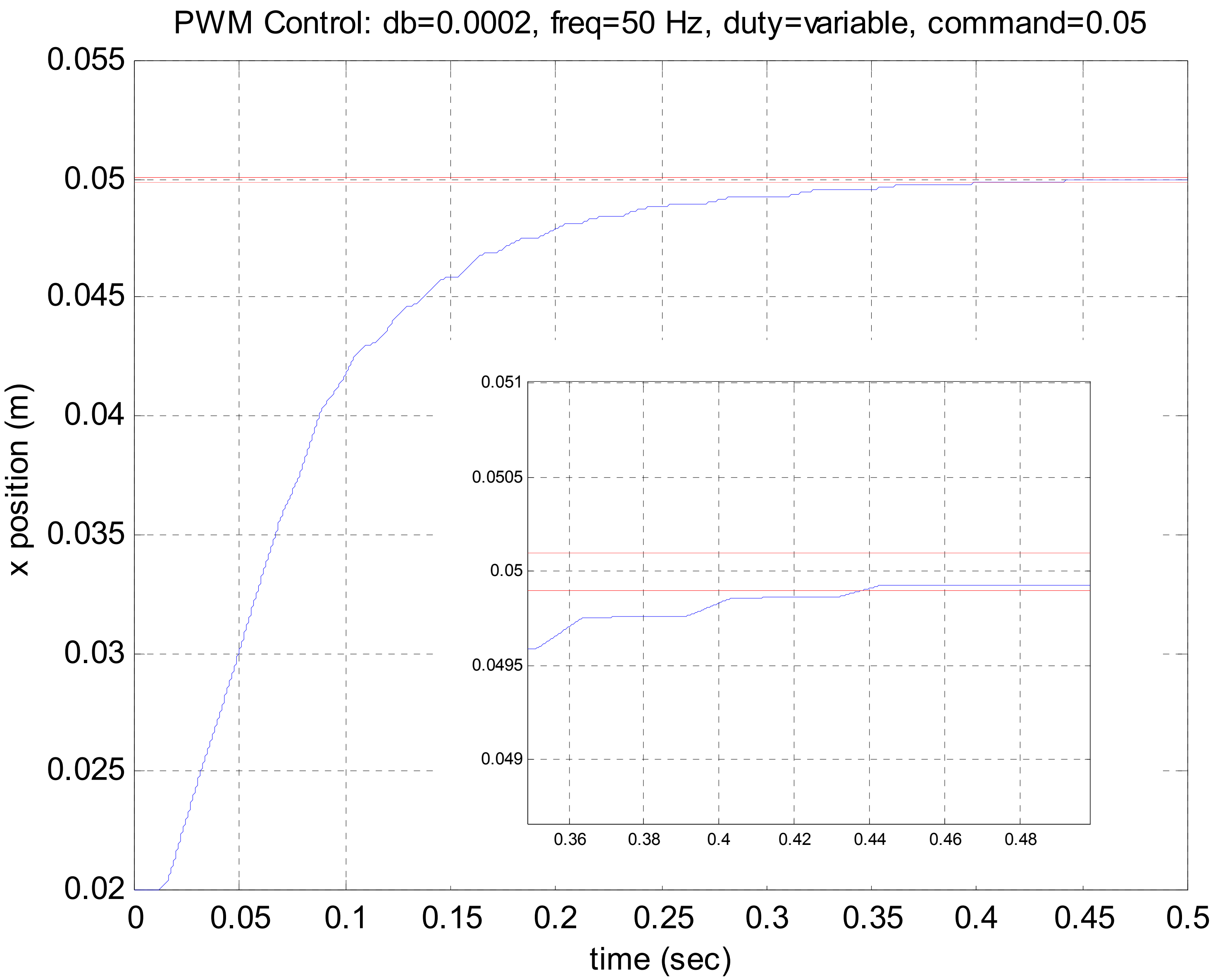


Modified On-Off Control: db=0.00075, pb=0.02, freq=50 Hz, duty=25%, command=0.05

PWM Controller




PWM Control: db=0.00075, freq=50 Hz, duty=variable, command=0.05
x position (m)
time (sec)
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5


PWM Control: db=0.0002, freq=50 Hz, duty=variable, command=0.05
x position (m)
time (sec)
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.051
0.0505
0.05
0.0495
0.049
0.36
0.38
0.4
0.42
0.44
0.46
0.48