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Modeling and Pressure Control in Microfluidic System

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ABSTRACT: This paper presents modeling and pressure control in a three lane micro fluidic system. A dual loop control system is employed .Which consists of an inner loop position controller and a pressure controller in the outer loop. By controlling the inlet pressure of the micro fluidic device the position of laminar flow interface between parallel streams in micro fluidic network can be controlled. Initially PID controller is used in both inner loop and outer loop. Then the inner PID controller is replaced by Fuzzy logic controller. Fuzzy based controller develops a control signal based on rule base. Finally a Neuro fuzzy controller is used as inner loop position controller and PID controller is used as outer loop pressure controller. Simulations are done in MATLAB and its results shows that when Neuro fuzzy controller is used as position controller the settling time and overshoot is greatly reduced.

KEYWORDS: Micro fluidics, Linearization, Fuzzy logic controller, Neuro fuzzy controller.

I. INTRODUCTION

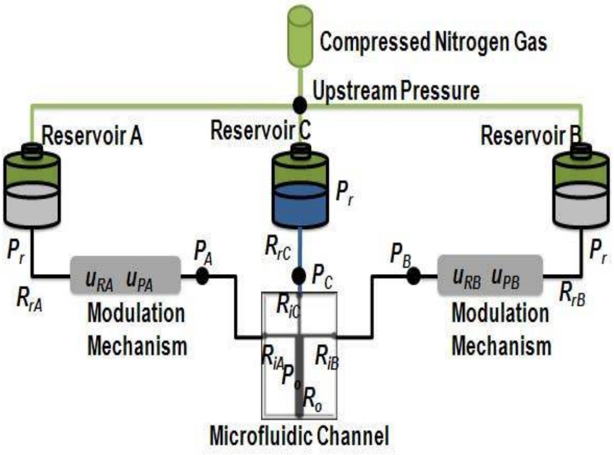
The branch of science and technology of systems which manipulates small amount of fluids using channels with dimension of micrometers is called Micro fluidics science. In this scienece devices have been used in different applications because of several advantageous features including a reduction in chemical volumes needed, the ability to control laminar flow interfaces and their fabrication is easy. Micro fluidic techniques widely used for many studies on physical and biochemical phenomena. Conventional micro fluidic systems using syringe pump has drawback of slow response time when setting a new flow rate and also flow oscillations. Flow changes can take second to hours. This lack of reactivity is one of the main limitation of syringe pump for numerous applications. Micro fluidic researchers predominantly use pressure controllers when they require high flow responsiveness, high flow stability and precision. Moreover when they work with dead end channels or require large sample volume.

In this paper, a three lane micro fluidic system is considered, and which has three lane micro fluidic channel, where fluids from three inlets converge and flow alongside one another, forming three different lanes in the outlet channel which is suitable for delivering substances selectively to specific regions in the outlet channel. For controlling pressure a new mechanism is developed[1]. A mechanically coupled variable resistance and variable volume reservoir is modulated by this mechanism for pressure control. A multi loop control system is employed which consists of position controller in the inner loop and an outer loop pressure controller. This brief present’s system Description and modelling, linearization, PID controller, Fuzzy controller and Neurofuzzy controller

II. SYSTEM DESCRIPTION AND MODELING

Nonlinear pressure model

Control system is developed for a three inlet/single outlet microfluidic network.Figure1 represents schematic of the pressure regulating system. Figure 2 shows the Fluidic circuit diagram of the system.



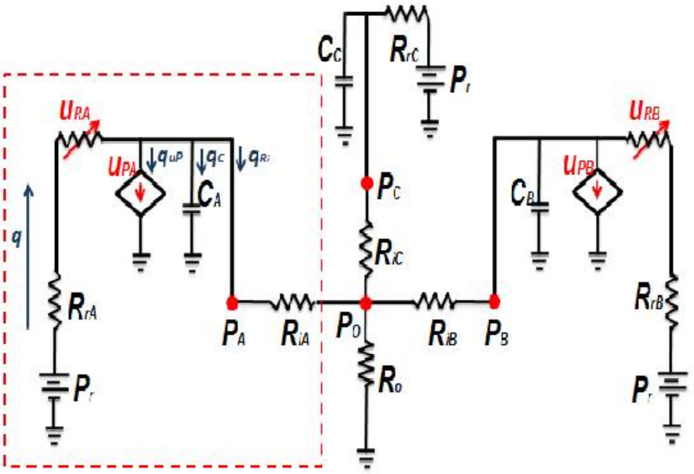


Figure.1 Schematic of pressure regulation system

Figure.2 Fluidic circuit diagram

NOMENCLATURE

q - Flow rate
Pr- Upstream reservoir pressure
P-Channel inlet pressure
C-Constant fluidic capacitance of a fluidic network
Rr-Constant fluidic resistance between a reservoir and a channel
Ur-Variable fluidic resistance
Up- Squeeze pump, or variable reservoir volume change over time
Ri- Constant fluidic resistance at the channel inlet
Ro-Constant fluidic resistance at the channel outlet
Vp- Volume of a fluidic network
V_g-Volume of a fluidic network when a inlet pressure is equal to atmosphere pressure

The subscripts A and B indicates the two outer fluid streams whose pressures at their channel inlets are controlled.To derive the dynamic model in a three lane system,consider the total flow rates from the three inlets

$$q_0 = qR_{iA} + qR_{iB} + qR_{iC} \qquad (1)$$

The total flow rate is also equal to the pressure drop over the resistance of the outlet channel

$$q_0 = \frac{p_0}{R_0} \qquad (2)$$

Since the outer streams A and B have the same mechanisms and fluidic component,the same dynamic model is derived for the outer streams A and B by suppressing the subscripts.Each flow rate is divided into three flow rates as shown in the dashed rectangle

$$q = q_{up} + qR_i + qc \qquad (3)$$

Equations (4) and (5) represents two of the flow in terms of pressure difference and resistance

$$q = \frac{p_r - p}{R_r + U_R} \qquad (4)$$

$$qR_i = \frac{p}{R_i} \qquad (5)$$

Equation (6) shows the flow in terms of a squeeze pump using the variable reservoir and a capacitance in the network

$$q_{up} + q_C = \frac{dV_p}{dt} = \frac{d(V_g + PC)}{dt}$$

$$= \frac{dV_g}{dt} + C\frac{dp}{dt} \qquad (6)$$

Where V_P is the volume of the fluid network

V_g is the volume of the fluidic network when the inlet pressure is equal to atmospheric pressure.

Assume that $\frac{dc}{dt}$ =0 .Substituting (4)-(6) in equation (3)

$$\frac{P_r}{R_r + U_R} - \frac{P}{R_r + U_R} = \frac{P}{R_i} + \frac{dv_g}{dt} + C\frac{dp}{dt}$$

$$\frac{dp}{dt} = -\left[\frac{1}{R_i c} + \frac{1}{(R_r + U_R)C}\right]P + \frac{1}{(R_r + U_R)C}P_r - \frac{1}{C}\frac{dV_g}{dt} \qquad (7)$$

Mechanism Principle and Operation

Figure.3 shows the pressure modulation mechanism concept and device operation. A large tube branch is added to the main flow path as an alternative flow path which is called variable reservoir, allowing the fluid to quickly drain from the main stream. Then the system response speed is improved and variable reservoir act as a squeeze pump. The modulation mechanism consists of a Four bar linkage and a DC motor.

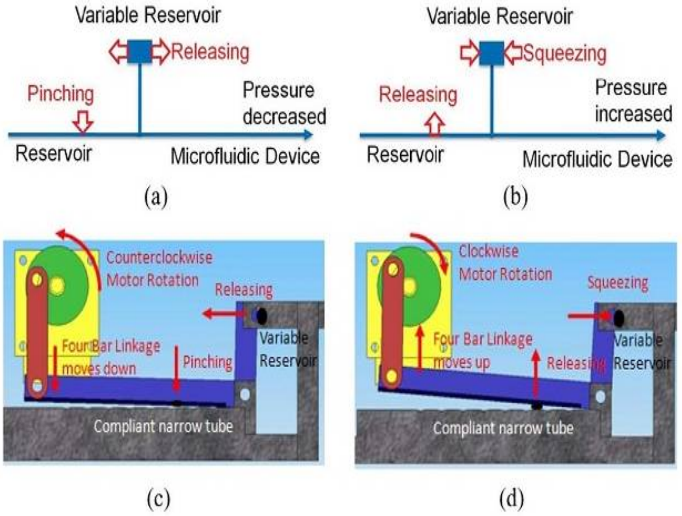


Figure.3 .Pressure modulation mechanism concept and device operation. (a) Pressure modulation concept for pressure decrease. (b) Pressure modulation concept for pressure increase (c) Mechanism device operation for pressure decrease. (d) Mechanism device operation for pressure increase.

When the pressure decreases, the motor rotates in counter clock wise direction and which causes one linkage moves down and the other linkage moves left. Which will causes pinching the narrow tube and when pressure increases, the motor rotates clockwise, one linkage moves up and the other moves right, results in the releasing of the narrow tube. At the inlet to the micro fluidic channel the downstream pressure can be regulated.

III LINEARIZATION

Model with coupled variable resistance and squeeze pump

$$\frac{dp}{dt} = -\left[\frac{1}{R_i C} + \frac{1}{(R_r + U_R(\theta)C}\right]P + \frac{1}{(R_r + U_R(\theta)C} P_r - \frac{1}{C}\frac{\partial V_g(\theta)}{\partial \theta}\dot{\theta}$$
$$= F(P, \theta, \dot{\theta})$$

The system operates in the vicinity of a set point where the dynamics can be approximated as linear and is given by the vector matrix form

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$
$$x = \begin{bmatrix} x1 \\ x2 \end{bmatrix} = \begin{bmatrix} P \\ \theta \end{bmatrix}$$
$$u = \dot{\theta}$$
$$\frac{dx_1}{dt} = \frac{dp}{dt}$$
$$\frac{dx_2}{dt} = \frac{d\theta}{dt} = \dot{\theta}$$
$$\frac{dx_1}{dt} = \frac{dp}{dt} = F(x, u) = F(P, \theta, \dot{\theta})$$

Define perturbations of the state variables.and take the derivative of the perturbed state by expanding in a Taylor series and neglecting higher order terms

$$\frac{d}{dt}(\delta x) = \frac{dF}{dP}\delta P + \frac{dF}{d\theta}\delta\theta + \frac{dF}{d\dot{\theta}}\delta\dot{\theta}$$

The matrix form is

$$\frac{d}{dt}(\delta x) = \frac{d}{dt}\begin{bmatrix} \delta P \\ \delta\theta \end{bmatrix} = A\begin{bmatrix} \delta P \\ \delta\theta \end{bmatrix} + B\delta U . \quad \text{Where}$$

$$A = \begin{bmatrix} dF/dP & dF/d\theta \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} dF/d\dot{\theta} \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \end{bmatrix}$$

TRANSFER FUNCTION

The transfer function from the angular velocity of motor to the pressure P at the inlet of microfluidic channel is

$$G(s) = \frac{P(s)}{\theta(s)} = SC[SI - A]^{-1}B$$

$$G(s) = -\frac{\frac{dV_g(\theta)}{d\theta}s + \frac{dU_R(\theta)}{d\theta}\frac{(P_r - P_0)}{[R_r + U_R(\theta)]^2}}{C\left(s + \frac{R_r + U_R(\theta) + R_i}{[R_r + U_R(\theta)]R_i}\right)}$$

Parameters in the Non linear pressure model

Table 1

Parameters		**Value**	**Unit**
P_r	Upstream pressure	20.6	kPa
P_o	Downstream pressure	15.1	kPa
R_r	Upstream Resistance	$1x10^{10}$	Pa s/m^3
C	Microchannel Capacitance	$7.6x10^{-12}$	m^3/Pa
R_i	Microchannel Resistance	$8.5x10^{14}$	Pa s/m^3
U_R	Variable resistance	$3.1x10^{14}$	Pa s/m^3
$dV_g/d\Theta$	Derivative of Vg w.r.t Θ	$-4.8x10^{-9}$	m^3/deg
$dU_R/d\Theta$	Derivative of UR w.r.t Θ	$-9x10^{13}$	Pa s/m^3 deg

The parameters in the Non linear pressure model is given in Table1

Substituting the values of Table1 in the Transfer function equation of dynamic pressure model

$$G_{RP}(s) = \frac{P(s)}{\theta(s)} = 1.2E3\frac{9.3E2S + 1}{1.7E3S + 1}$$

DC Motor and mechanism

Table 2

Parameters		**Value**	**Unit**
J_m	Moment of inertia of motor	$7.1x10^{-6}$	Kgm^2/s^2
B_m	Damping ratio	$3.5x10^{-6}$	Nms
L_m	Electric Inductance	$5.1x10^{-4}$	H
R_m	Electric Resistance	$6.8x10^{-1}$	ohm
K_t	Electromotive force constant	$1.7x10^{-2}$	Nm/Amp
J_d	Moment of inertia of mechanism	$3x10^{-4}$	Kgm^2/s^2
K_d	spring constant of mechanism	1	N/m
B_d	Damping ratio of mechanism	$1x10^{-1}$	Nms

Physical parameters used in the dc motor and mechanism are given in Table2

The Transfer function of the motor and mechanism is $\frac{\theta(s)}{V(s)} = \frac{K_t}{\Delta(s)}$ where

$$\Delta(s) = J_{eq}L_m s^3 + [J_{eq}R_m + L_m B_{eq}]s^2 + [B_{eq}R_m + K_d L_m + K_t{}^2]s + K_d R_m$$

$$J_{eq} = J_m + J_d, B_{eq} = B_m + B_d$$

Transfer function of the dc motor is

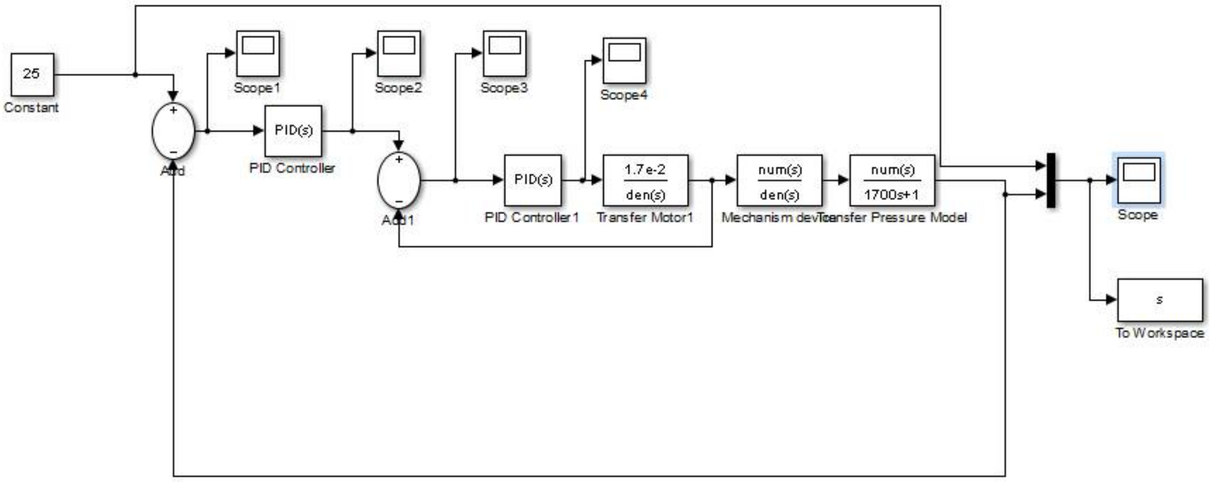
$$G_M(s) = \frac{1.7*10^{-2}}{3.621*10^{-9}S^3 + 4.829*10^{-6}S^2 + 2.9138*10^{-4}S}$$

Transfer function of the mechanism is = $\dfrac{6.156*10^{-11}S^3+8.209*10^{-8}S^2+4.953*10^{-6}S}{2.663*10^{-9}S^3+4.417*10^{-6}S^2+0.00117S+0.01156}$

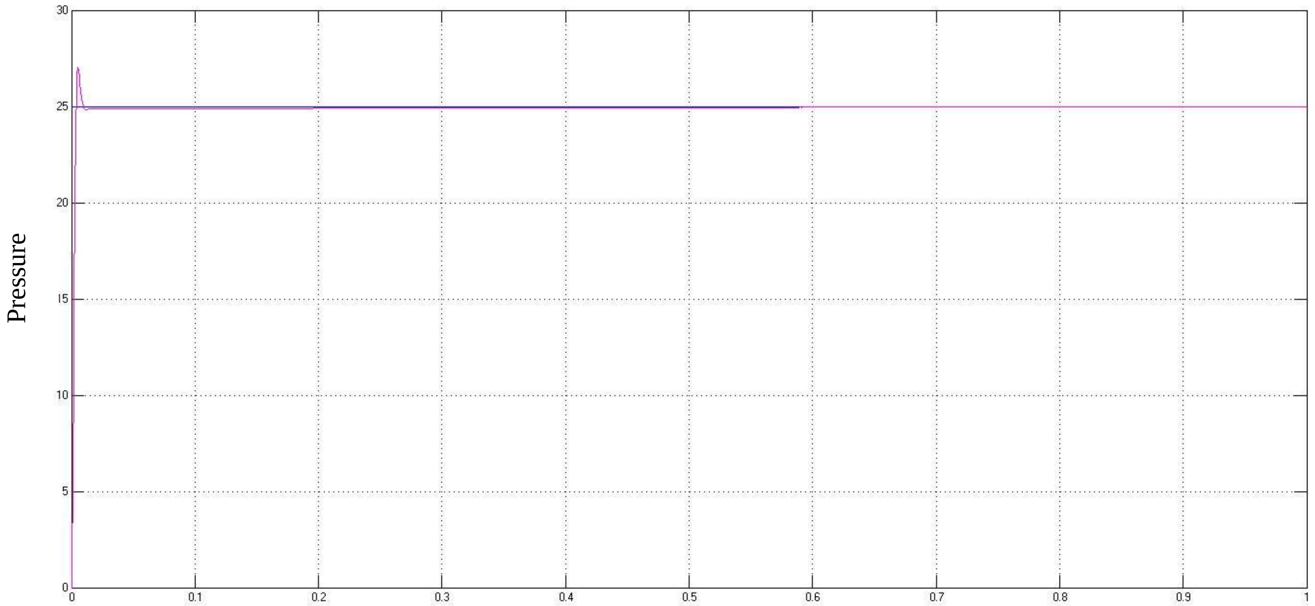
1V. RESULT AND DISCUSSION

PID CONTROLLER

One PID controller is used as inner loop position controller.and another PID controller is used as outer loop pressure controller.The simulink block diagram consisting of two PID controllers is shown.



A constant pressure of 25kpa is given as input.The following figure shows the simulation result.Simulation result shows that the settling time is 0.6seconds and overshoot is 2.1 .

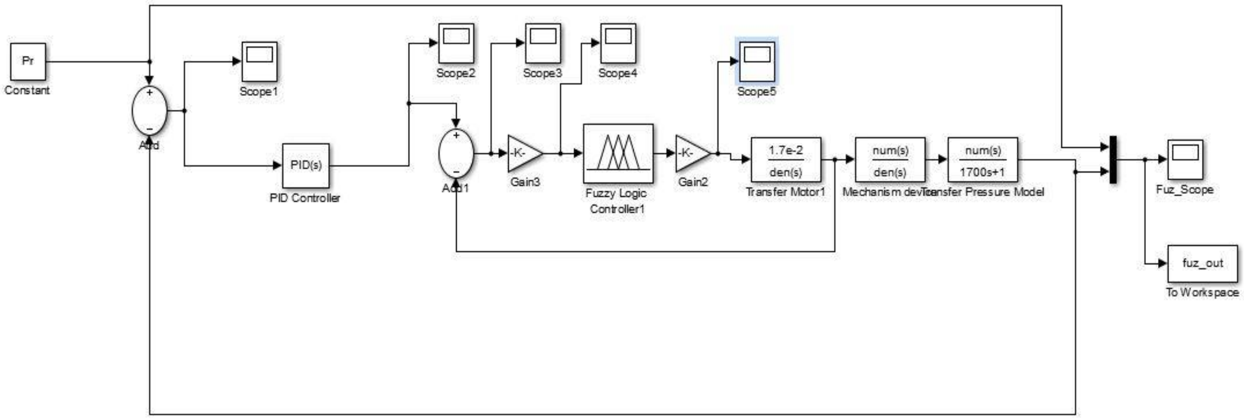


Simulation result of two PID controllers

FUZZY LOGIC CONTROLLER

Fuzzy logic controllers extensively used for various control system applications. The advantages of Fuzzy logic controllers are it is flexible, easy to understand, tolerant of imprecise data and it can be blended with conventional control techniques. Fuzzy logic controller's work on the bases of a list of IF-THEN statements called Rules. Here Fuzzy logic controller is used as inner loop position controller and PID controller is used as outer loop pressure controller. The Rule base and member ship functions are the main parts of fuzzy logic controller. Mamdani inference model and. Gaussian member ship functions are used here for input and output. Seven membership functions with linguistic variables NB, NM, NS, PS, PM, PB are used here to represent a single input single output system. The fuzzy Rule base is following.

- If the error is NB then control output is NB
- If the error is NM then control output is NM
- If the error is NS then control output is NS
- If the error is Z then control output is Z
- If the error is PS then control output is PS
- If the error is PM then control output is PM
- If the error is PB then control output is PB

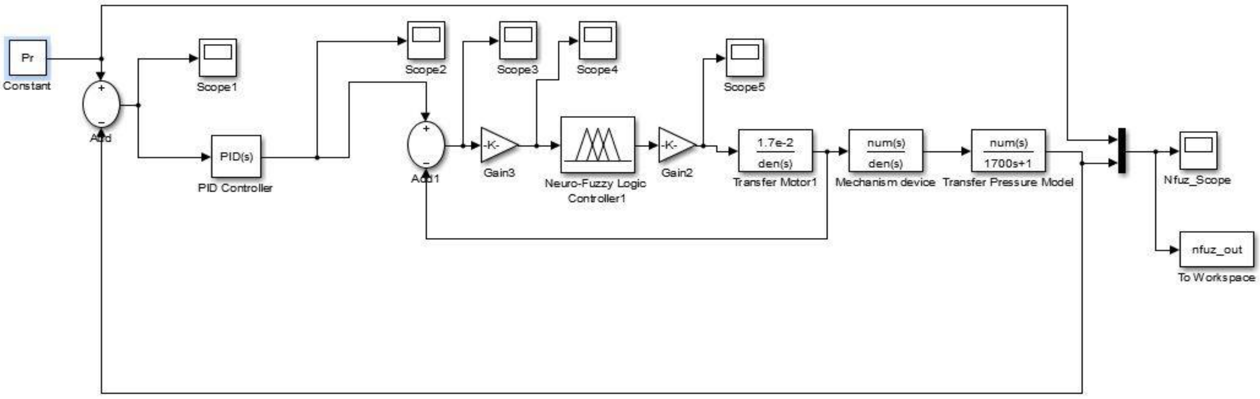


Simulink Block diagram of Fuzzy Logic Controller

The above figure shows the simulink block diagram containing an inner loop fuzzy logic controller and an outer loop PID controller.

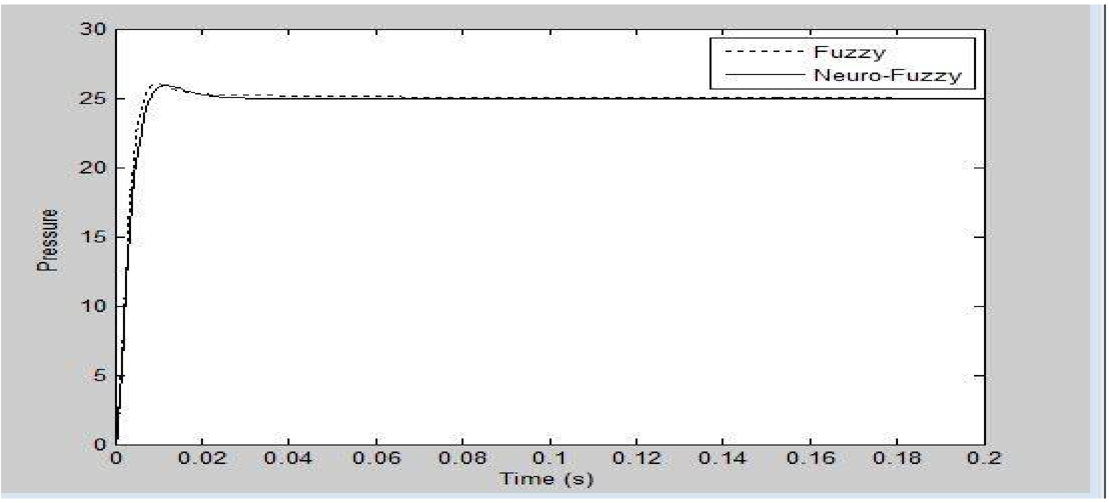
NEURO FUZZY CONTROLLER

Neuro Fuzzy Controller combines the advantages of both neural network and fuzzy logic .Neuro fuzzy controller uses the learning techniques of neural network to tune the membership function and form the Rule base of Fuzzy logic controller.ANFIS[Adaptive Neurofuzzy Inference System] is used for the development of neuro fuzzy controller.ANFIS uses hybrid learning algorithm . Hybrid learning algorithm is a combination of back propagation algorithm and least square method for training data set.Sugeno type Fuzzy inference system is used. The member ship functions which are used to represent input is Gaussian .Seven member ship functions are used to represent the input and output. They are represented as NB, NM, NS, PS, PM, and PB. Training is an important step for the formation of proper rule base and parameter tuning.In Sugeno type inference system output is a function of input.Here a neuro fuzzy controller is used in the inner loop and PID controller is used in the outer loop.



Simulink Block diagram of Neuro Fuzzy Controller

The above figure shows the simulink block diagram containing an inner loop neuro fuzzy controller and an outer loop PID controller



Simulation Result

A constant pressure of 25kpa is applied as input.The simulation result shows that for fuzzy logic in position control the settling time is 0.18 seconds and overshoot is 1.1.When neuro fuzzy is used the settling time is 0.03 seconds and overshoot is reduced to 0.7.

V.CONCLUSION

From the simulation results it can be concluded that the the proposed system having Neuro fuzzy controller act as position controller in the inner loop and PID controller as pressure controller in the outer loop significantly reduces the settling time and overshoot.Table 3 shows performance comparison of different controllers.

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Table 3

Parameter	PID	Fuzzy logic in position controller	Neuro Fuzzy logic in position controller
settling time	0.6	0.18	0.03
over shoot	2.1	1.1	0.7
Rise time	0.005	0.007	0.0075

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