A Fuzzy Logic Controller for Thrust Level Control of Liquid Propellant Engines

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***Abstract*— Thrust level control of liquid propellant engines is investigated in this paper. The dynamic equations of liquid propellant engines are formulated and a PID and a fuzzy controllers are designed to control its thrust level. Fuzzy logic deals with problems that have intrinsic or informational imprecision in definition of objective function or constraints. So fuzzy controller can be a good choice to control nonlinear systems like liquid propellant engine. Both PID and fuzzy controllers can control the engine thrust level well. Their performances are compared and investigated.**

***Keywords*— fuzzy control; liquid propellant engine; thrust level control.**

I. INTRODUCTION

Liquid Propellant Rocket Engines (LPRE) are used in various operational Launch Vehicles all over the world. Based on the type of propellants used, they are classified as Earth-storable, Semi-cryogenic and Cryogenic rocket engines [1]. LPRE's are also classified as pump-fed engines and pressure–fed engines based on the propellant feed system. The Liquid Rocket Engine consists of Thrust chamber, propellant feed system, control components, ignition system, pre-conditioning system, control system etc. The control systems ensure proper functioning of the engine system with the desired performance. The basic Liquid-Propellant-Engine Control Systems are [3]:

- Engine start sequence control
- Engine cut off sequence control
- Engine duration control
- Engine safety control
- Propellant-tank pressurization control
- Engine-system Checkout and test controls
- Thrust vector control by gimballing the engine.
- Engine thrust-level control
- Propellant mixture ratio / Propellant utilization control

The control systems interconnect the components and logics designed to yield a desired response or output based on a command or reference input. Selection of the control method best suited for the propulsion system is influenced by the performance requirements, accuracy, and dynamic characteristics of the engine being controlled and particularly by engine reaction-time. This paper investigates mathematical modeling of combustion chamber and gas generator and then designing controllers for thrust level control of the engine.

Thrust vector control by Gimballing LPREs:

Steering of a vehicle over the desired trajectory employs thrust vector control systems (TVC). One of the methods of TVC is by gimballing either the main engine or by Gimballing vernier engines. Based on the vehicle trajectory the onboard computer generates the necessary error signal and gimbals the main engine using actuators. This topic is not in scope of this paper.

Thrust and Mixture Ratio Control (MRC) Systems:

As the Liquid Propellant engine and stage systems are configured and the propellant is loaded considering the optimum thrust and mixture ratio requirements, it is possible to achieve the safe engine operation, required vehicle performance and minimum propellant outage only if the engine is operated at the specified thrust and mixture ratio. Deviation from the requirements could be caused by factors such as engine tuning error, deviation in pressure and temperature of propellants at engine inlets etc. Deviation in thrust and mixture ratio can lead to either under performance and additional propellant outage or engine malfunctioning and failure. In order to ensure safe engine operation and optimum performance of the vehicle, it is essential to regulate the thrust and mixture ratio within the specified limits. Engine thrust and mixture ratio may be controlled by controlling the propellant flow to the engine, either in open loop mode or closed loop mode.

Thrust Control Schemes:

In pressure fed engine, pre-calibrated flow control devices such as orifices or venturies are used in the propellant feed circuits, to maintain the thrust within the specified limits in open loop mode and variable area flow control valves in the feed circuits or propellant tank pressure variation is used for controlling the thrust in close loop mode [2]. In pump-fed

Engines the thrust is regulated by controlling the power generated by the turbines by controlling the flow rate to the turbines. In the open-loop thrust control mode, pre-calibrated flow control elements are used for controlling the throughput to the turbines. In the case of GG cycle or staged combustion cycle engines, the propellant flow to the GG/ Pre Combusting Chamber (PCC) is controlled using fixed area orifices or venturies. Similarly in the case of engines working on other cycles, the thrust control is achieved by using pre-calibrated control elements in the turbine feed lines. In the closed loop control mode, flow to the turbine is controlled by variable area flow control valves. The thrust of the GG/SCC engines may be regulated either by controlling the propellant flow to the GG/PCC or by adjusting the hot gas flow from GG/PCC outlet to the turbines. The engine thrust is controlled in closed loop mode, by using either engine parameters (chamber pressure or propellant injection pressure) or vehicle parameters (vehicle acceleration or incremental velocity) as feedback signals [9].

Earth storable engines generally employ pneumo/hydraulic systems for thrust and mixture ratio control. Thrust is controlled by controlling the chamber pressure. The thrust control regulator uses a piston, balanced by the chamber pressure feedback on one side and the required chamber pressure fed as command pressure on the other side. Any unbalance will move the piston thereby changing the propellant flow rate to gas generator resulting in an increase or decrease in chamber pressure as required. Since the effect of propellant temperature on mixture ratio is negligible, the mixture ratio is controlled by controlling the thrust chamber inlet pressures. The mixture ratio control regulator equalizes the oxidizer and fuel pressures at thrust chamber inlet by means of a balancing piston. The required mixture ratio is ensured by suitably sizing the calibrated orifice mounted in the propellant line.

There are limited references in the open literature on the design of a combustion chamber control system. A class of literature on dynamic analysis and control system design for liquid propellant engines is limited to linear models of the engine utilizing a linear systems theory [5],[6]; therefore such designs would not be as robust as if the design were based on a nonlinear model of the engine. In the other class a nonlinear system design approach is employed utilizing nonlinear systems design techniques for use with reusable rocket engines and the design of the regulator loop is assumed to be based on a standard robust design that is used for linear systems [7]. The work presented herein for the design of the regulator control loop is based on a simplified mathematical model of the engine thrust force. The contribution of our work includes to show efficiency of fuzzy controller to adjust thrust level of LPREs.

II. MATHEMATICAL MODEL

LPRE is composed with combustor, turbopump, turbine, control valve, gas generator, pipes and so on as Fig. 1. In development phase, thrust control is one of the important requirements of LPRE. Also, mixture ratio control of propellants fed into combustor and gas generator is needed for safe operation of LPRE. For control of LPRE, 3 control valves are installed at the LOX line of gas generator, the main LOX line and the main fuel line of combustor.

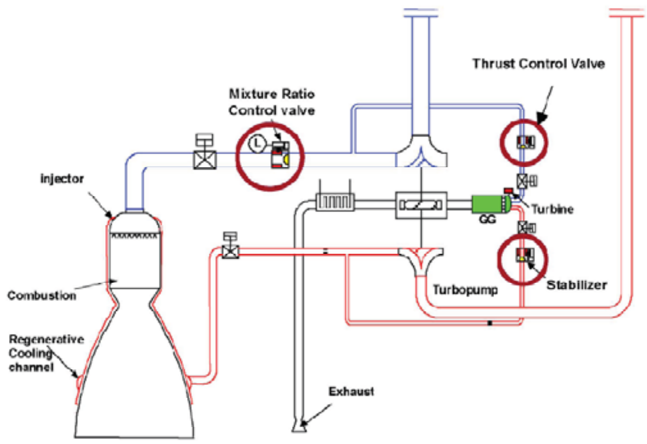

Fig. 1. Schematic of open type LPRE [4]

These simplifying assumptions have been considered in mathematical modeling:
The flow is incompressible,
Effects of temperature variations are ignored,
The output pressure of fuel and oxidizer tanks remain constant,
Flow density and viscosity is considered constant,
Gas flow in combustion chamber and gas generator is assumed to be adiabatic and non-viscous.

2.1 Main combustor and gas generator

In both main combustor and gas generator, combustion occurs and we take use of the outlet gas pressure, therefore their model are similar. We start with continuity equation for the gas inside combustion chamber or gas generator:

$$\dot{m}_{in}(t-\tau)=\dot{m}_{out}(t)+\frac{dm}{dt} \quad (1)$$

in which $\dot{m}_{in}$ is propellant flowrate into the chamber, $\dot{m}_{out}$ is outlet flowrate of propellant from the chamber, τ is combustion time constant and m is the mass of propellant inside the chamber. In this equation we have

$$\dot{m}_{in}(t-\tau)=\dot{m}_{ox}(t-\tau)+\dot{m}_{fu}(t-\tau) \quad (2)$$

So,

$$\dot{m}_{in}(t-\tau)=\dot{m}_{fu}(t-\tau)+\dot{m}_{ox}(t-\tau)=\dot{m}_{out}(t)+\frac{dm}{dt} \quad (3)$$

With the assumption of ideal gas

$$\mathrm{m}=\frac{\mathrm{PV}}{\mathrm{RT}} \quad (4)$$

If we assume that RT is constant, derivation of equation (4) yields to

$$\frac{dm}{dt} = \dot{m}_{in}(t-\tau) - \dot{m}_{out}(t-\tau) = \frac{V}{RT}\frac{dp}{dt} \qquad (5)$$

In combustion chamber and gas generator, characteristic velocity is defined as

$$C^* = \frac{P.A_t}{\dot{m}_{out}} \qquad (6)$$

and characteristic length is defined as

$$L^* = \frac{V}{A_t} \qquad (7)$$

Therefore characteristic velocity is written as

$$C^* = \frac{\sqrt{R.T}}{\Gamma} \qquad (8)$$

in which

$$\Gamma = \sqrt{k}\left[\frac{2}{k+1}\right]^{\frac{k+1}{2(k-1)}}. \qquad (9)$$

Substituting these equations into (5) we will have

$$\frac{dm}{dt} = \frac{L^* A_t}{C^{*2}\Gamma^2}.\frac{dp}{dt} \qquad (10)$$

Substituting equations (6) and (10) into (3) yields to

$$\frac{L^* A_t}{\Gamma^2 C^{*2}}\frac{dp}{dt} + \frac{A_t}{C^*}P_{cc} = \dot{m}_{in}(t-\tau) = \dot{m}_{fu}(t-\tau) + \dot{m}_{ox}(t-\tau) \qquad (11)$$

This is the equation of combustion process. This equation is based on steady combustion and evaporation time is neglected.

2.2 Turbopump

In turbopump complex, the high pressure outlet gas from gas generator rotates turbine and this rotation is transferred to pumps of the main fuel and oxidizer lines.

Dynamic equation of torque is

$$TQ_{turbine} - TQ_{pump,fu} - TQ_{pump,ox} = J_{eq} \times \dot{\omega} \qquad (12)$$

In which $TQ_{turbine}$ is turbine generated torque, $TQ_{pump,fu}$ and $TQ_{pump,ox}$ are consumed torques of fuel and oxidizer pumps, J_{eq} is equivalent moment of inertia of turbine and $\dot{\omega}$ is angular acceleration of its shaft.

The pump model using Avsianikeve equation is

$$\frac{H}{\omega^2} = (A + B(\frac{Q}{\omega}) - C(\frac{Q}{\omega})^2)/g \qquad (13)$$

In which H is pump head, Q is flowrate, ω is angular velocity of pump and g is the gravity.

2.3 Pipelines and valves

Losses of flow is due to friction ΔP_f and resistances in flow path ΔP_R.

$$\Delta P = \Delta P_f + \Delta P_R \qquad (14)$$

$$\Delta P_f = f\frac{L}{d}\frac{\rho V^2}{2} \qquad (15)$$

$$\Delta P_R = k\frac{\rho V^2}{2} \qquad (16)$$

In which ρ is density of fluid, V is its velocity, f is friction coefficient, L is length of pipe, d is its diameter and k is coefficient of minor losses.

2.4 Thrust control valve

The model of valve body can be simply written as

$$\dot{m} = K_v\sqrt{2\rho\Delta P}$$
$$L_v = \frac{1}{T_v s + 1}U_v \qquad (17)$$
$$K_v = A_v e^{0.04L_v}$$

2.5 The overall model of LPRE

The overall model can be composed using above equations.

III. DESIGN OF PID CONTROL SYSTEM

The control system consists of pressure control of combustion chamber for thrust control of LPRE. The pressure of combustion chamber is controlled with thrust control valve operated by PI control or fuzzy control. Now having the simplified thrust model in Simulink we can design controllers. Fig. 2 shows the model and controller. Since there is restriction for flowrate of fuel and oxidizer we have used a saturation block after PID controller to restrict control signal in acceptable range.

Proportional–integral–derivative (PID) control of the engine was attempted first, since it is a popular closed-loop control approach that can be applied to a wide range of engineering problems.

Using automated PID tuning in Matlab SISO tool, this optimized PID controller was obtained:

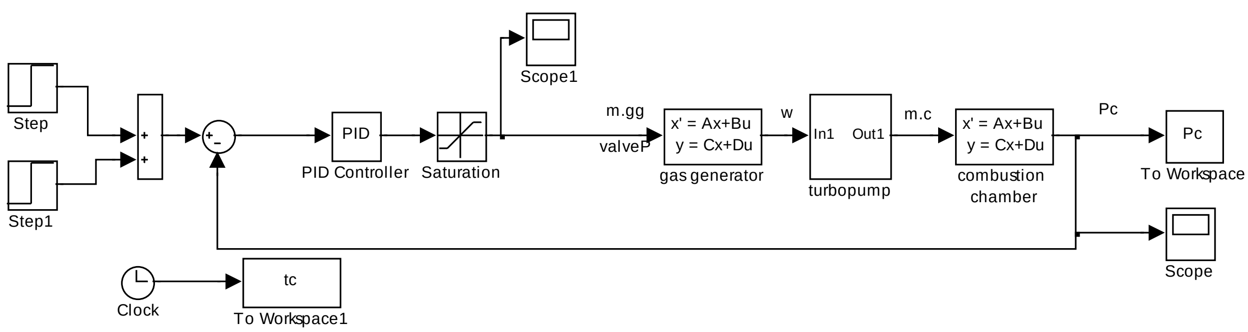

Fig. 2. PID control system of thrust level

$$C = 0.00016 \times \frac{(1 + 2.6\times10^{-5} s)(1 + 4.2\times10^{-4} s)}{s}$$

Figs. 3,4,5 show root locus, bode diagram and step response of this controller.

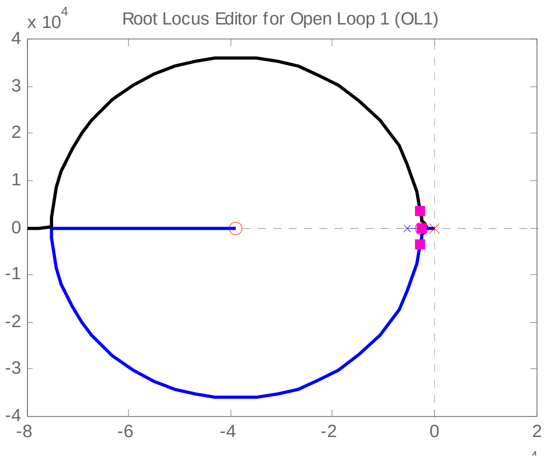

Fig. 3. Open loop root locus with optimized PID controller

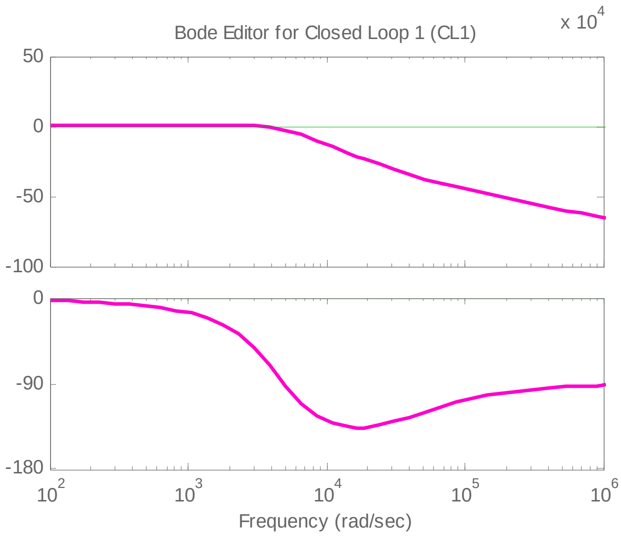

Fig. 4. Closed loop bode diagram with optimized PID controller

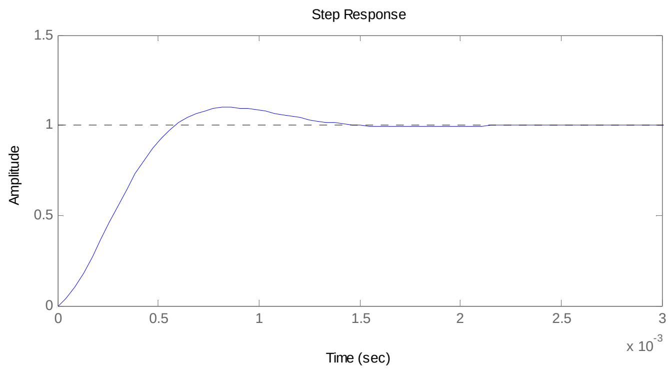

Fig. 5. Step response with optimized PID controller

IV. FLC Design and Application

The employment of fuzzy techniques belongs to the "soft computing'' family of algorithms. Here "soft computing'' refers to computational mechanisms that can determine suitable relationships (in a system data set) to assess and determine a quantitative opinion(s) based on future conditions. Within MSFC, such computational mechanisms are viewed as a collection of algorithms that can achieve optimal or near-optimal results in the presence of imprecise data, uncertainty [8], unknown physics, and probabilistic outcomes. The central goal in soft computing is to obtain greater robustness to these and other uncertainties.

Similar to the PID design, for main thrust level control, a FLC is designed and the response of the engine to a step input using the PID and fuzzy controllers is compared. The use of fuzzy logic is seen to be suitable since it accommodates the uncertainties associated with the engine. The technology of fuzzy logic enables a computer to make decisions based on vagueness or imprecision intrinsic in most physical systems. Fuzzy logic also provides a convenient way to introduce useful nonlinearities into the control law to achieve specific effects, such as reducing large overshoots.

A fuzzy controller was designed with two inputs and one output. The input variables used in the design of the controller were thrust error (e) and thrust error rate (ei). The thrust error is defined as the desired thrust minus the actual thrust in pounds. The thrust error rate is the change in thrust error in one sampling interval. The defined membership functions

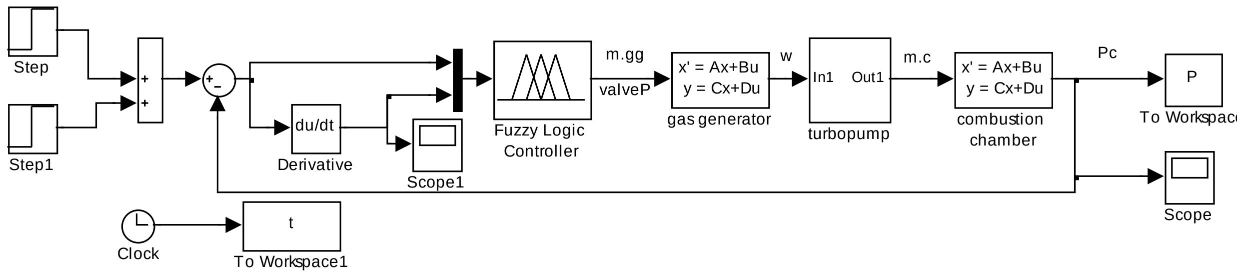

Fig. 6. Fuzzy control system of thrust level

have been shown in Figs. 7-9. We have used Gaussian membership functions for e and triangular membership functions for $\dot{e}$ and control valve position.

Our rule-base consists of ten fuzzy rules that have been constructed using heuristics and experience, as follows:

- 1. If (e is pF) then (V is pH) (1)
- 2. If (e is nF) then (V is nH) (1)
- 3. If (e is pC) then (V is pM) (1)
- 4. If (e is nC) then (V is nM) (1)
- 5. If (e is Z) then (V is Z) (1)
- 6. If (e is pN) then (V is pL) (1)
- 7. If (e is nN) then (V is nL) (1)
- 8. If (ei is nL) then (V is nM) (1)
- 9. If (ei is Z) then (V is Z) (1)
- 10. If (ei is pL) then (V is pM) (1)

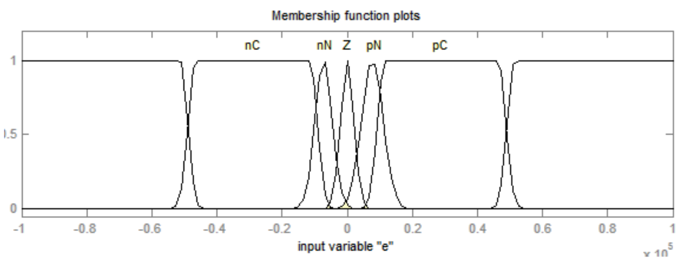

Fig. 7. membership functions for e

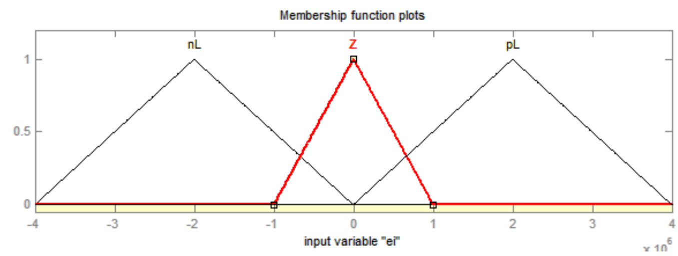

Fig. 8. membership functions for $\dot{e}$

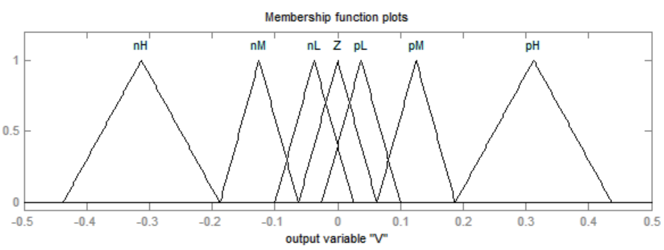

Fig. 9. membership functions for valve position

We define a desired P_c with two steps and apply our optimized PID controller and designed fuzzy controller to this input. The desired chamber pressure values are 40bar, 43bar and 45bar. Results are shown in Figs. 10-13. It can be seen that the controlled thrust of optimized fuzzy controller has less oscillations than fuzzy controller, but both of the controllers have an acceptable performance.

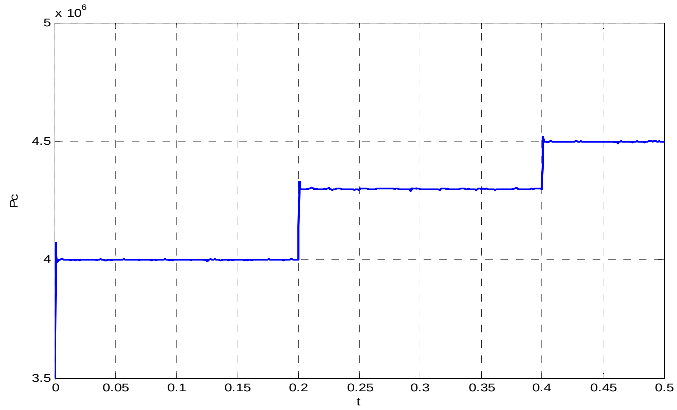

Fig. 10. Controlled chamber pressure using PID controller

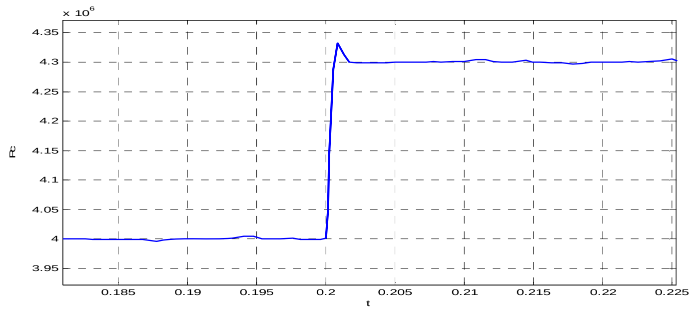

Fig. 11. Controlled chamber pressure using PID controller (zoomed)

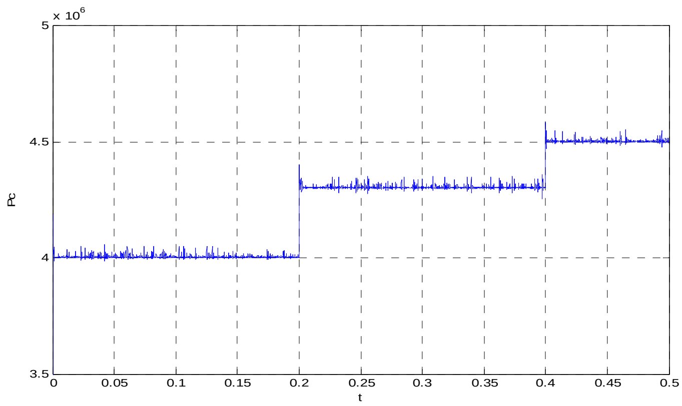

Fig. 12. Controlled chamber pressure using fuzzy controller

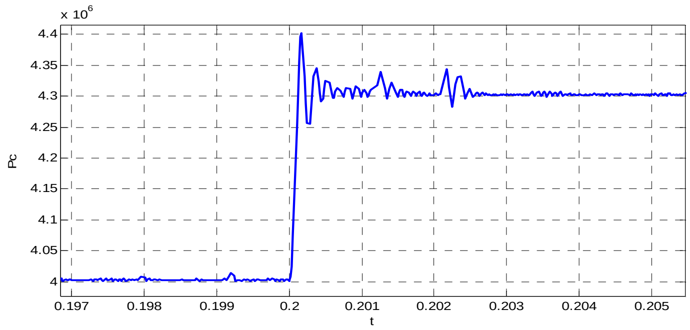

Fig. 13. Controlled chamber pressure using fuzzy controller (zoomed)

V. CONCLUDING REMARKS

The mathematical model of LPRE was established with the 1st order ordinary differential equations. For the control of thrust level of LPRE, we established two control systems, an optimized PID controller with saturators and a fuzzy controller using the parameters of the optimized PID controller to choose the values of fuzzy membership functions. We defined a desired chamber pressure with two constant levels and applied the controllers to adjust the pressure. Both of the controllers have an acceptable performance but the optimized PID controller had overall better results. This has two reasons; first, the parameters of PID controller was optimized but parameters of fuzzy controller was chosen using the optimized PID controller results but they were not directly optimized; second, we have used simplifying assumptions to model the motor with linear differential equations. Actual LPRE is a nonlinear system and probably the designed fuzzy controller will has better results if implemented on real motor, because fuzzy controller is robust against uncertainties and nonlinearities.

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