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2-Loop Nonlinear Dynamic Inversion Fuel Flow Controller Design for Air-to-Air Ducted Ramjet Rocket

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ABSTRACT

Fuel Flow controller based ramjet propulsion system have a flexibility to change rocket velocity depending on guidance requirement by controlling the fuel flow rate as a function of atmospheric conditions like altitude, Mach no. and angle of attack. In this paper, Design objectives & requirements of fuel flow controller have been brought out from guidance loop for air-to-air target engagement. 2-loop non-linear dynamic inversion (DI) based controller design has been proposed to track the commanded thrust and to meet the time constant requirement as a function of altitude, Mach no. and angle of attack. The outer thrust loop is to control commanded thrust and to generate the demand for gas generator pressure loop and inner pressure loop is to meet outer loop demand by controlling throttle valve area. The engine state space plant model has been adapted with improvement of existing model. Throttle valve actuator specifications requirement are also brought out.

Keywords: Ducted ramjet; PN guidance; 2-Loop fuel flow controller; Gas generator; Throttle valve

NOMENCLATURE

V_M	Rocket velocity, m/sec
T_{ap}	Autopilot time constant, sec
ω_{ap}	Bandwidth of Autopilot, rad/sec
T_{seeker}	Seeker data process lag, sec
$T_{estimator}$	Estimator (EKF) lag, sec
P_g	Gas generator pressure, N/m^2
R_g	Specific gas constant, J/kg-K
T_g	Gas generator temperature, K
γ	Flight path angle, deg
θ	Rocket orientation angle, deg
ρ_a	Air density, kg/m^3
V_a	Sound velocity, m/sec
C_D	Drag coefficient
C_L	Induce drag coefficient
A_{tr}	Throttle valve area
P_c	Demanded Combustion pressure
M_s	Sensed Mach number
M_d	demanded Mach number

1. INTRODUCTION

Ramjet engine are potential source of power supply especially for high speed supersonic long range air-to-air rocket. Performance of ramjet engine is highly depending on flight operating conditions like altitude, Mach no and angle of attack. To achieve demanded thrust as a function of operating flight conditions, effective fuel flow control is required. The function of fuel flow controller is to open the throttle valve for variation of propellant from gas generator and burn in combustor chamber in presence of air flow from intake to generate 1- The desire thrust to meet guidance requirement, 2- Mach number control at every altitude, 3- To meet time constant requirement of guidance loop.

For control design, the first step is the modelling of plant. Many literatures[1-3] are available, which discussed about propulsion modelling of ducted rocket and about its components like gas generator, throttle valve and combustor chamber as shown in Fig. 1. These papers clearly brought out the relation between throttle area, burning rate of gas generator propellant, gas generator pressure and fuel flow rate to combustion chamber. However, they have not talked about the controller of ramjet using throat area as control input.

There are many literatures available which talked about controller for ramjet ducted rocket in[4-6]. In all papers, PID based single set of controller gain for fuel flow controller has been designed to meet objectives. However these gains are inadequate to provide the desired performance for wide range of operation.

In[7], author has proposed FFC design using variable throttle valve and using variable gas generator pressure through pneumatic pressure (pressure balance mode) with help of PID. However, this needs extra hardware which lead to complexities in small rocket design.

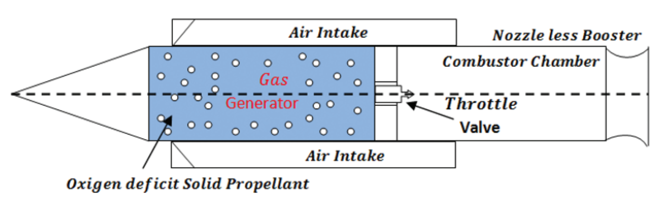

Figure 1. Schematic diagram of ducted Rocket.

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Further work has been done in[9-11], where two loop based thrust controller has been proposed (Outer loop as thrust control loop and inner loop as pressure control loop). Mathematical model of both loop have been obtained in space state equation. In reference[9], a new fusion feedback input from gas generator pressure and combustion pressure is discussed to ensure stability. In reference[10,11], authors brought out PID controller gain scheduling based on look-up table and they also shown comparison with PI controller vs. adaptive controller and made conclusion that both controller performance are satisfactory.

However, controller design of above all works have carried out standalone mode and not accounted the following aspect: 1- Design objectives of FFC, 2- Effect of angle attack at state space engine model and 3- FFC performance at various altitude and Mach no to meet design objective, 4- Throttle valve actuator requirement.

In this paper, authors have tried to solve above problem by introducing the following works;

(i) Design objectives of FFC from guidance loop as a function of operating condition, which gives
   (a) Speed of response (Time constant) and steady state error requirement
   (b) Actuator specification
(ii) Effect of angle of attack in engine dynamics modelling.
(iii) Gains scheduling as function of operating conditions to meet fuel flow controller design objectives.

PN based guidance has been considered for generating FFC requirement at different engagement scenario, which is a robust guidance for aerial target application. Generally, tactical rocket do manoeuvre while engaging target, that lead to have high angle of attack which tend to give induced drag and effect on the thrust requirement. So, existing engine mathematical model has been improved for design. 2-loop non-linear dynamic inversion based controller design is scheduled for controller gain which is updated automatically based on operating condition and maintain stability and performance.

2. GUIDANCE LOOP REQUIREMENT FOR FFC

Ramjet rocket has to engage aerial target from low altitude to high altitude. Based on target manoeuvre capability as a function of altitude & Mach no., PN based guidance can generate legitimate lateral acceleration demand in presence of autopilot, seeker and estimator lag to intercept the target for a given range-to-go as shown in Fig. 2. Where Rmin (H) is minimum rage-to-go, $V_T(H)$ and $\eta_T(H)$ are target speed and manoeuvre as a function of altitude[12]. PN guidance collision course works optimally for constant velocity. Autopilot lag depends on rocket normal force coefficient, altitude, Mach no and angle of attack.

In general, configuration of rocket design is carried out to satisfy guidance demand and autopilot time constant. During engagement, rocket cruise velocity reduce due to angle of attack (induce drag) build up to meet lateral accelerate demand. Reduction in velocity further increase the angle of attack.

Increased angle of attack also deteriorate the performance of thrust generation due to low capture of mass flow air into the combustion process. It would further lead to reduce velocity. Finally mission miss distance requirement gets affected.

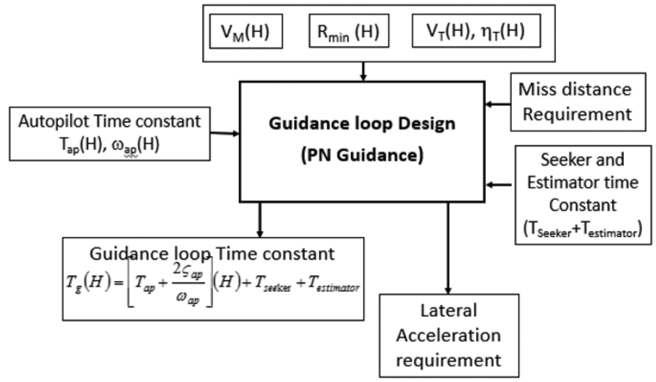

Figure 2. Schematic diagram of guidance loop.

So, velocity (Thrust) requirement and rate of change of velocity to be achieved in guidance loop for maintaining rocket velocity. Therefore, Speed of response of fuel flow controller (T_{ffc}) is depended on guidance time constant (T_g) as a function of altitude and Mach no.

$$T_{ffc}(H) = T_g(H) \tag{1}$$

To achieve speed of response of fuel flow controller as a function of altitude, actuator speed of response can be computed based on the minimum time constant of FFC. Minimum time constant requirement of controller would be needed at low altitude engagement scenario. Fuel flow controller have 2-loop based structure for thrust generation. Based on loop separation theory, 4 time separation need between thrust loops (Outer) to pressure loop (Inner). However,

$$\text{Gas pressure loop bandwidth} = \frac{4}{T_{ffc\_min}} \tag{2}$$

where T_{ffc_min} is fastest time constant needed at low altitude.

Further actuator situated in inner loop of pressure loop with faster plant dynamics. So 4-5 times separation is to be ensured for actuator to maintain stability. So,

$$\text{Actuator bandwidth} = \frac{16-20}{T_{ffc\_min}} \tag{3}$$

Generally, Thrust loop (Guidance loop) BW vary from 1.0 Hz to 3.0 Hz , so gas pressure loop should be around 4 Hz to 12 Hz. And actuator requirement of FFC should be 20 Hz to 45 Hz.

3. MATHEMATICAL MODELLING OF DUCTED ROCKET

The ducted rocket mainly comprises of gas generator dynamics for gas flow, a combustion engine dynamics for thrust generation and actuator dynamics for movement of throttle valve. So modelling of ramjet engine components as shown in Fig. 3 are constituted. Combustion engine dynamics provide thrust based on fuel flow rate, static pressure and temperature.

Basically, throttle valve open through the actuator based on the error generated by thrust control loop to release fuel flow rate. Generation of fuel flow rate depends on dynamic condition of gas generator. The working principle of fuel flow rate control depends on following conditions

(i) When the throttle area reduces, it will increase the gas generator pressure and fuel flow rate of gas increase.

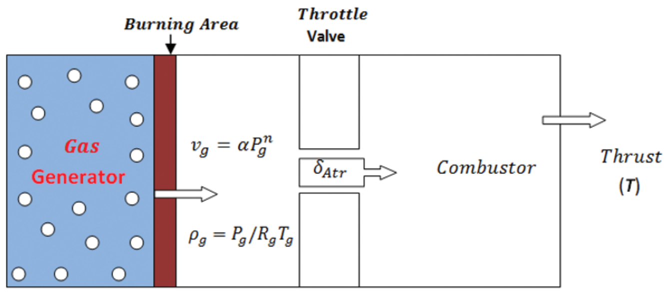

Figure 3. Schematic diagram of ramjet engine.

(ii) Burning rate of solid propellant in gas generator is proportional to the chamber pressure of gas generator.

(iii) So, Reduction of throttle valve area through actuator will be generated more gas burning and produce more fuel flow rate.

The gas generator propellant is designed as a cigarette burning with a constant area (A_g) is -

$$\dot{m}_g = \rho_g A_g \upsilon_g \tag{4}$$

where, $\rho_g = P_g / R_g T_g$ is the density of propellant and $\upsilon_g = \alpha P_g^n$ is the burn rate of the propellant.

The variation of gas generator volume will be

$$\dot{\upsilon}_g = A_g \upsilon_g \tag{5}$$

In gas generator burning progress of the propellant vacant free volume of gas generator and it will be filled with hot gases. Then the gas start flowing from the gas generator to the combustion area through the throttle valve.

Now, the flow fuel rate of gas through the throttle valve is

$$\dot{m}_{flow} = \frac{P_g A_{tr}}{C_g} \tag{6}$$

where, C_g is characteristic velocity of solid propellant. Then, Incremental change in fuel flow rate is

$$\Delta\dot{m}_{flow} = \frac{P_{g0}\Delta A_{tr}}{C_g} + \frac{A_{tr0}\Delta P_g}{C_g} \tag{7}$$

where, A_{tr} is a function of throttle valve opening area.

The gas generator dynamics is given by,

$$\dot{P}_g = \frac{R_g T_g}{V_g}\left(\dot{m}_g - \dot{m}_{flow}\right) \tag{8}$$

Incremental relation can be obtained from the above relation

$$\Delta\dot{P}_g = \frac{R_g T_g}{V_g}\left(\rho_g A_g \alpha P_{g0}^{n-1}\Delta P_g - \frac{P_{g0}\Delta A_{tr}}{C_g} - \frac{A_{tr0}\Delta P_g}{C_g}\right) \tag{9}$$

Gas generator propellant is designed as cigarette burning, so the characteristic velocity of solid propellant C_g to be constant. And from above equation gas flow rate capacity can be written as

$$\frac{\dot{m}_{m\_max}}{\dot{m}_{m\_min}} = \left(\frac{A_{tr\_max}}{A_{tr\_min}}\right)^{\frac{n}{n-1}} \tag{10}$$

From the above equation, conclusion can be drawn that the gas flow capacity depends on the propellant characteristic regardless of the throttle area ratio.

Now, The Gas generator dynamics are:

$$\Delta\dot{P}_g = \frac{R_g T_g}{V_g}\left(\rho_g A_g \alpha P_{g0}^{n-1}\Delta P_g - \frac{P_{g0}\Delta A_{tr}}{C_g} - \frac{A_{tr0}\Delta P_g}{C_g}\right) \tag{11}$$

$$\Delta\dot{m}_{flow} = \frac{P_{g0}\Delta A_{tr}}{C_g} + \frac{A_{tr0}\Delta P_g}{C_g} \tag{12}$$

The longitudinal equation of rocket motion is defined by Newton's law

$$m\frac{dV}{dt} = T + L_D + D + G \tag{13}$$

where m is mass of rocket, V velocity, L and D is the lift, G is gravity force and drag force of rocket as function of Mach and angle of attack as shown in Fig. 4. Gravity is small quantity so it can be neglected.

Equation can be written as;

$$mV_a\Delta\dot{M} = \Delta T - \frac{n}{2}P_s\left(C_D\cos\alpha - C_L\sin\alpha\right)\Delta M \tag{14}$$

Induce Drag and Drag force can be

$$L = \frac{n}{2}P_s C_L \Delta M \ \ and\ D = \frac{n}{2}P_s C_D \Delta M$$

For an isentropic fluid, $V_a = \sqrt{n\frac{P_s}{\rho}}$

Generated thrust by engine

$$T = f(Ps, Ts, M, \alpha, \dot{m}_{flow}) \tag{15}$$

where Ps and Ts are the static pressure and temperature.

Linearisation of a thrust equation can be written as

$$\Delta T = \frac{\partial T}{\partial \dot{m}_g}.\Delta\dot{m}_g + \frac{\partial T}{\partial M}.\Delta M \tag{16}$$

After solving above equation, the thrust model is:

$$\Delta\dot{M} = \frac{A_{tr0}}{V_a m C^*}\frac{\partial T}{\partial \dot{m}_g}\Delta P_g + \frac{\dot{P}_{ro}}{V_a m C^*}\frac{\partial T}{\partial \dot{m}_g}\Delta A_{tr} +$$

$$\frac{1}{mV_a}\left(\frac{\partial T}{\partial M} - \frac{n}{2}P_s\left(C_D\cos\alpha - C_L\sin\alpha\right)\right)\Delta M \tag{17}$$

ΔA_{tr} factor contribution is not prominent in above Eqn (17).

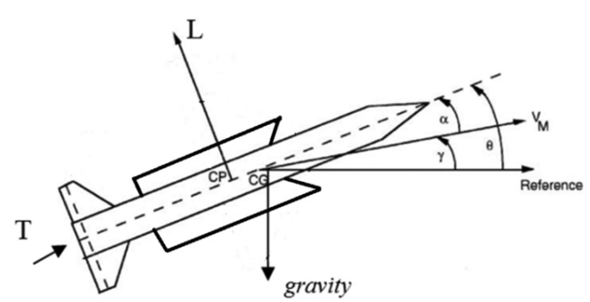

Figure 4. Representation of ducted Rocket schematic diagram.

By solving above equation, the state space representation of engine in the form

$$\dot{X} = AX + BU,$$

where , $X=\left[\Delta P_g \;\; \Delta M\right]^T$ and $U = \Delta A_{tr}$

X = State variables, U = Control input

$$A = \begin{bmatrix} \frac{R_g T_g}{V_g}\left(\rho_g A_g a P_{g0}^{n-1} - \frac{A_{tr0}}{C_g}\right) & 0 \\ \frac{\dot{A}_{tr0}}{V_a m Cg}\frac{\partial T}{\partial \dot{m}_g} & \frac{1}{mV_a}\left(\frac{\partial T}{\partial M} - \frac{n}{2}P_s\left(C_D\cos\alpha - C_L\sin\alpha\right)\right) \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{R_g T_g}{V_{g0}}\frac{P_{r0}}{C_g} \\ \frac{\dot{P}_{g0}}{V_a m C_g}\frac{\partial T}{\partial \dot{m}_g} \end{bmatrix}$$

4. TWO LOOP FUEL FLOW CONTROL DESIGN USING NON-LINEAR DYNAMIC INVERSION (DI)

The basic concept behind time scale separation DI controller is to follow commanded input with desired fastness and accuracy when original plant can be thought of as one fast dynamic and one slow dynamics. It can be achieved by inverting the governing equations of the individual dynamics based on measured state and input command.

let the nonlinear system is written as:

$$\dot{x} = F(x,u) \tag{18}$$

Using time scale separation fast state and slow state can be separated as :

$$\dot{x}_s = f_s(x) + g_s(x)x_f \tag{19}$$

$$\dot{x}_f = f_f(x) + g_f(x)u \tag{20}$$

where $x = [x_s, x_f]$ are slow and fast state variables.

Above equation clearly shows that for slow state dynamics, fast state dynamics appears as input. Following equation can be written from out of plant

$$\begin{aligned} \dot{Y} &= \frac{\partial y}{\partial x_s}\dot{x}_s \Rightarrow \frac{\partial y}{\partial x_s} f_s + \Delta_s x_f \\ where,\ \Delta_s &= \frac{\partial y}{\partial x_s} g_s(x) \end{aligned} \tag{21}$$

Now based on desired output and sensed output, the desired output dynamics can be designed as;

$$\dot{Y}_d = f(Y_d, Y, \omega_s, \xi_s) \tag{22}$$

where ω_s and ξ_s are the desired natual frequency and damping of outer loop or slowly varying output control loop. Based on desired dynamics of slow states, desired input to faster dynamics can be obtained from equation- 18 as;

$$x_{fd} = \Delta_s^{-1}\left(\dot{Y}_d - \frac{\partial y}{\partial x_s} f_s\right) \tag{23}$$

here, Δ_s must be invertible. Now this desired fast state is used to design the desired fast state dynamics as:

$$\dot{x}_{fd} = f(x_{fd}, x_f, \omega_f, \xi_f) \tag{24}$$

Now fast dynamics is inverted to obtain control input as:

$$u = g_f(x)^{-1}\left(\dot{x}_{fd} - f_f(x)\right) \tag{25}$$

Figure 5, shows the loop architecture designed for fuel flow controller of ducted ramjet system. It is having 2-loop structure. The outer loop is called a thrust control loop and it is having slow dynamics characteristic. Inner loop is called pressure control loop and it is having fast dynamics characteristic. Based on outer loop demand, slow loop dynamic formulation can be computed the desired demand for fast loop. To ensure it, fast loop dynamics formulation will generate control requirement.

The main task of the controller is to track the commanded thrust and meet desire speed of response during cruise Phase and acceleration Phase of rocket.

Outer loop design

The Outer control loop has the requirement from guidance loop to achieve the velocity and speed of response.

The desired dynamics are:

$$\dot{M}_g = \omega_{outer}(M_d - M_s) \tag{26}$$

where, $\omega_{outer} = 1/T_{ffc}$ time constant of outer loop.

So, from Eqn (17), the demanded gas generator pressure can be computed as:

$$P_{gc} = \frac{\Delta\dot{M}_g - \frac{1}{mV_a}\left(\frac{\partial T}{\partial M} - \frac{n}{2}P_s S(C_N + C_D)\right)\Delta Mg}{\frac{Atr0}{V_a mC^*}\frac{\partial T}{\partial \dot{m}_g}} \tag{27}$$

here $T_{ffc} = f(V_m, H, mass, C_{n\alpha}, T_f)$, $C_{n\alpha}$ and mass depends on ducted rocket configuration and V_m and H (altitude) on trajectory. T_f is tuning factor depends on guidance phase.

Inner loop design

Gas generator pressure control loop receive the requirement from outer loop. To meet, the desire dynamic condition can be written as:

$$\dot{P}_{gc} = -2\zeta_g\omega_g P_{gs} + \omega_g^2\int\left(P_{gs} - P_{gc}\right)dt \tag{28}$$

where, ζ_g and $\omega_g(\approx 3.5\omega_{outer})$ is required damping ratio and speed of response (natural frequency) of inner loop which is scheduled based on time scale separation between fast loop to slow loop. P_{gc} and P_{gs} is commanded and sense gas generator pressure.

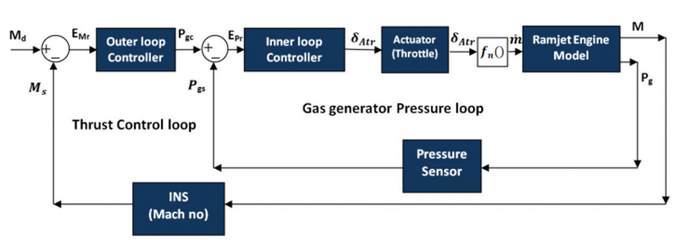

Figure 5. Representation of 2-loop Block diagram of FFC.

So, from Eqn (11), the demanded throttle open area is:

$$\Delta A_{tr} = \frac{\Delta \dot{P}_g - \left[\frac{R_g T_g}{V_g} \left(\rho_g A_g \alpha P_{g0}^{n-1} \right) + \frac{A_{tr0}}{C_g} \right]}{\frac{P_{g0}}{C_g}} \tag{29}$$

Throttle area incremental opening ensures requirement of fuel flow rate to fulfil the desired thrust.

It should be ensured that ducted rocket could work stable and reliable with designed control system to ensure the time domain performance like steady state (within ±2.0%) of all flight operation condition.

5. SIMULATION RESULTS ANALYSIS AND DISCUSSION

In this section, 2-loop non-linear dynamic inversion based fuel flow controller and engine plant modelling is carried out in simulation environment in ideal condition (isotropic gas assumption) with actuator, sensor and delay. The design of controller need to be enough stable to cater the uncertainties over ideal assumption.

Simulations have been carried out to show the performance of DI based fuel flow controller for meeting the Mach no. demand. Speed of response (T_{ffc})has been computed based on operating conditions. It is low value for lower altitude and high value for higher altitude. All results like Mach no, gas generator pressure, throttle area and time are normalised.

Figures 6, 7 and 8 shown the performance comparison of 2-loop fuel flow controller of Mach no, gas generated pressure dynamics and throttle area.

It is clearly seen that speed of response of both cases achieved as per demand requirement and response shows the design performance of non-linear dynamic inversion controller.

To achieve mach no demand, outer loop design relation generate the demand of gas generator pressure P_{gc} for inner loop. Inner loop design relation compute the rate of change of $\dot{P}_{gc}$ based on time scale separation between slow loop to fast loop. To meet $\dot{P}_{gc}$, dynamic inversion of inner loop dynamic generate the demand of throttle valve area. The gas generator pressure demand vs. feedback for both the cases is shown in Fig. 7 and similarly throttle valve area demand vs. feedback is shown in Fig. 8.

Authors also bring out the advantage of dynamic inversion (DI) FFC controller gain which is scheduled based on operating conditions against the fixed gain design for different engagement. In general, fuel flow controller design objectives is to have very less overshoot and steady state error. Fixed gain could be ensured a better performance at designed condition but it performance get deteriorate at other altitude condition.

Figure 9 shows that performance comparison of scheduled gain and fixed gain design of fuel flow controller.

Fixed gain based controller shows the similar performance at low altitude where it is made tuned but same gain performance at high altitude case is deteriorated and it bring requirement of high gas generator pressure which can lead to high combustion pressure and performance of ramjet will deteriorate or become unstable.

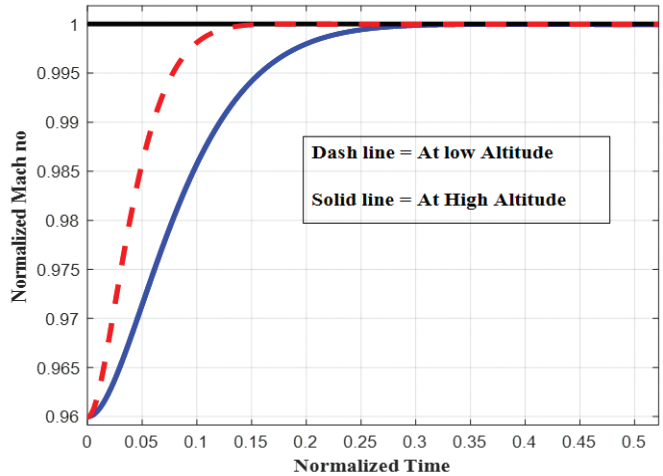

Figure 6. Mach no performance.

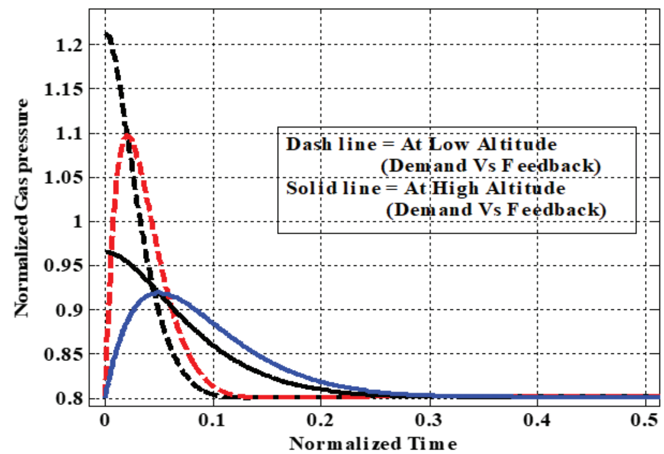

Figure 7. Gas generator pressure.

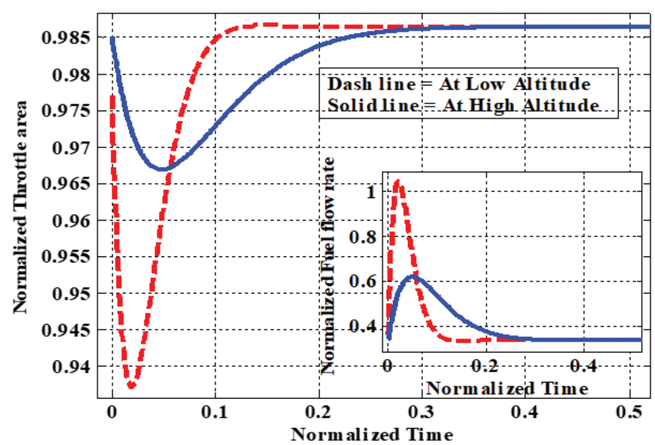

Figure 8. Throttle area and corresponding Fuel-rate.

6. CONCLUSION

This Paper brought out the fuel flow controller design requirements of different engagement scenario based on PN based guidance as a function of altitude and Mach no. To meet design objectives, 2-loop non-linear dynamic inversion (DI) based fuel flow controller have been designed and brought out actuator specification. Performance results shows that this design is ensuring time domain performance at different altitudes for aerial target where the dynamic coupling between

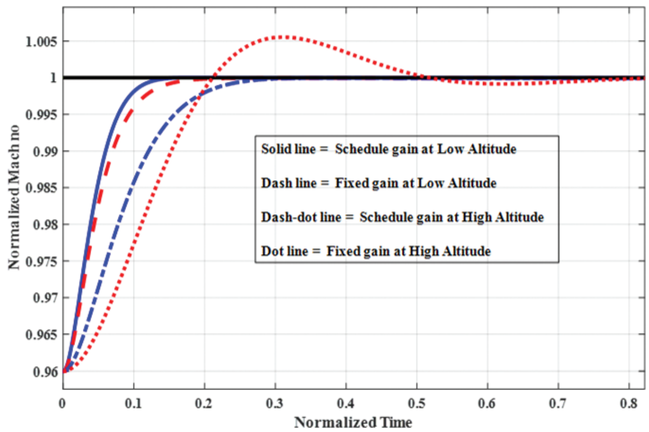

Figure 9. Scheduled gain Vs fixed gain performance at same altitude.

operating condition and engagement scenario makes design more challenging within the constraint. And also brought out scheduled gain as a function of operating condition advantage over fixed gain design for efficient operation of ramjet engine.

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CONTRIBUTORS

Mr Srikant Srivastava did his graduation from G.B. Pant Engineering College, uttarakhand and post-graduation from IIT Kharagpur in Electrical engineering. He has been working in DRDO, Hyderabad.
In the current study, he has performed exaustive litetature survey and carried out the detailed modelling of ramjet operartion and it's interaction with missile guidance with different inputs and design a controller and prepared the manuscript.

Dr P.N. Dwivedi did his graduation from IIT Kanpur and post-graduation and PhD from IISc Bangalore in Aerospace Science and Engineering. He has been working in DRDO, Hyderabad.
In the current study, he has given many valuable inputs at different stage of modelling and design. He has helped in analysing and validating the results.

Prof. D. Vinod Kumar, did his post-graduation from Osmania University Hyderabad, PhD from IIT Kanpur and Post-Doctoral from Howard University Washington, USA. He has been currently working as professor in department of electrical engineering NIT Warangal.
In this current study, he has given the idea, reviewed the work and continuously provided the guidance and given many valuable inputs.