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3-Loop Structure based Fuel Flow Controller Design for Robust Operation of Ducted Ramjet Rocket

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ABSTRACT

This paper is about the designing of 3-loop structure based fuel flow controller (FFC) for efficient operation of supersonic ramjet based propulsion system. The main objective of the control design is to vary appropriately the engine controllable parameters (throttle value area) such that commanded thrust is achieved by ramjet engine without endangering the engine stability and performance. Various factors such as combustion-intake interaction, atmospheric disturbance and other flight conditions have a significant impact on the air intake operation which lead to effect on engine performance. Due to above effect, intake un-start and buzzing phenomena can occur due to back pressure fluctuation and it disturb the intake pressure recovery and air mass flow rate. So, back pressure based extra loop introduce in 2-loop FFC design to have tight control on back pressure margin for smooth and efficient operation of air intake without need of extra hardware.

Keywords: Ducted ramjet; Air intake; Back pressure; Terminal shock; Throttle valve; Buzz phenomena

NOMENCLATURE

P_g	Gas generator pressure, N/m^2
R_g	Specific gas constant, J/kg-K
T_g	Gas generator temperature, K
α	Rocket angle of attack, deg
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
P_{cs}	Sensed Combustion pressure
M_s	Sensed Mach number
M_d	Demanded Mach number

1. INTRODUCTION

In general scenario, ramjet engine based ducted rocket provides supersonic power on interception for long range engagement of aerial target. A ramjet engine is air-breathing combustion system consisting of a gas generator housing the solid propellant, a throttle valve which regulates the fuel flow into the secondary combustion chamber, an air intake system, an exit nozzle and an integrated booster to start the ramjet engine (Fig. 1). A special characteristic of a solid propellant is that It burning depends on gas generator (GG) pressure so that flow of fuel rate is directly controlled by regulating the gas generator pressure. The functions of fuel flow controller (FFC) are 1- Achieve the desire thrust to meet trajectory requirement, 2- maintain fuel flow regulation within the safe operation air fuel ratio, 3-Prevention of reduction of flight Mach below the minimum Mach under which flight become impossible at all value of fuel consumption.

There are many papers[4-7] which talk about fuel flow controller which is based on 2-loop structure to meet ramjet thrust requirement. Outer loop as thrust control loop and inner loop as a GG pressure control loop. Gains of controller based on either single set gain or look-up table.

However above all paper talked about Fuel flow controller design considering ideal intake performance. Air intake operation leads a very important role for ramjet engine operation for thrust generation. But in flight scenario intake-combustion interaction and atmospheric disturbances, Intake performance effect on efficiency and stability of ramjet engine. Research describe[10] cause of intake un-start and it detrimental effect on engine operation. How the terminal shock position inside the intake responds to atmospheric disturbance at upstream and combustion disturbance in downstream. Above uncertainties and disturbances generally effect the intake back

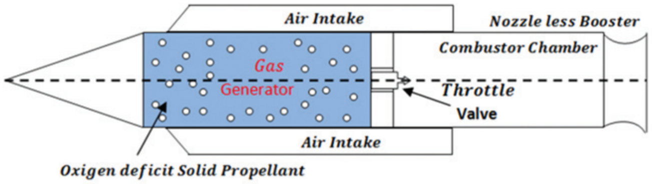

Figure 1. Schematic diagram of ducted Rocket.

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pressure, which is disturbed the terminal shock formation of intake[9, 11,12] at design location and it would lead either buzz oscillation or un-start phenomena. A supersonic intake Buzz phenomenon is undesirable oscillation that fluctuate air mass flow rate enter into intake. Controlling of un-start and buzz phenomena, Papers[13,15] were published to control intake un-start and buzz either through nozzle throat area or bleed movement at upstream control with support of extra hardware.

Generally, Air-to-Air rocket configuration has a tight constraint on space. Controlling/ avoiding of intake instability through nozzle throat area or bleed movement lead to extra hardware requirement. So, in this paper, author has found a solution to solve above problem without need of extra hardware. A novel approach technique is to introduce as a feed forward back pressure control loop into the 2-loop based fuel flow controller which is based on operational back pressure margin in air-intake design to handle intake instability like un-start and buzzing for efficient operation of thrust generation in ramjet engine.

2. MATHEMATICAL MODELLING OF DUCTED ROCKET

A schematic diagram for the ramjet engine components is shown in Fig. 2. The throttle valve is opened by a actuator which is controlled by the thrust control loop to generate the required amount of fuel mass flow rate to meet the demanded thrust. When the throttle valve area is less, the gas generator pressure rises up, which in turn increases the burning rate of the solid propellant and thus the fuel mass flow rate is high which generates greater thrust.

The solid propellant burning is a cigarette type burning with a constant burning area. The burnt mass of the solid propellant is given by [1, 2, and 3],

$$\dot{m}_{burn} = \rho_g A_g \upsilon_g \tag{1}$$

Where, $\rho_g = \dfrac{P_g}{R_g T_g}$ is the density of fuel gases and $\upsilon_g = \alpha P_g^n$ is the burn rate of the propellant.

The rate of volume change of the gas generator is given by

$$\dot{\upsilon}_g = A_g \upsilon_g \tag{2}$$

The free volume of the gas generator will be occupied by the burnt gases from the solid propellant and this burnt gases will flow through the throttle valve. The mass of the gas that will flow through the throttle valve is given by,

$$\dot{m}_{flow} = \frac{P_g A_{tr}}{C_g} \tag{3}$$

Where C_g is the characteristic velocity of the gases, A_{tr} is the throttle valve area and P_g is a GG pressure.

From (3), the incremental in flow rate can be formulated as

$$\Delta\dot{m}_{flow} = \frac{P_{g0}\Delta A_{tr}}{C_g} + \frac{A_{tr0}\Delta P_g}{C_g} \tag{4}$$

The gas generator dynamics is given by,

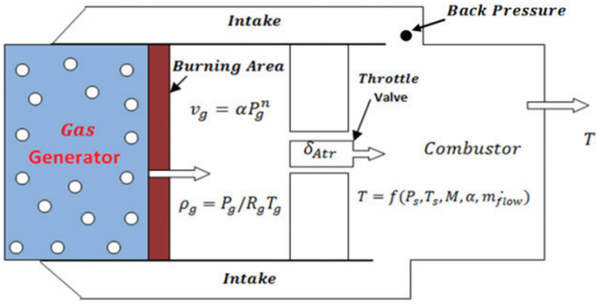

Figure 2. Schematic diagram of ramjet engine.

$$\dot{P}_g = \frac{R_g T_g}{V_g}\left(\dot{m}_{burn} - \dot{m}_{flow}\right) \tag{5}$$

Incremental relation can be obtained from the above relation as,

$$\Delta\dot{P}_g = \frac{R_g T_g}{V_g}\left(\Delta\dot{m}_{burn} - \Delta\dot{m}_{flow}\right) \tag{6}$$

Substituting (1) and (4) in the above equation we can obtain,

$$\Delta\dot{P}_g = \frac{R_g T_g}{V_g}\left(\rho_g A_g \alpha P_{g0}^{n-1}\Delta P_g - \frac{P_{g0}\Delta A_{tr}}{C_g} - \frac{A_{tr0}\Delta P_g}{C_g}\right) \tag{7}$$

Now let us consider the equation of motion for the missile. The longitudinal motion of the missile can be represented as in the schematic diagram. (Fig. 3)

The equation of longitudinal motion can be written as,

$$m\frac{dV}{dt} = T + L + D + Gravity \tag{8}$$

Where m is mass of the rocket, V velocity, L & D is the lift and drag force of rocket as function of Mach number and angle of attack. Gravity force can be neglected as it is small compared to the other forces.

Rewriting $V = M.V_a$ the above equation can be written as

$$mV_a\Delta\dot{M} = \Delta T - \frac{\gamma}{2}P_s\left(C_D^{'}\cos\alpha - C_L^{'}\sin\alpha\right)\Delta M \tag{9}$$

The supersonic drag and lift coefficient is an inverse function of Mach Number, Hence the lift and drag coefficient can be written as ,

$$C_L = \frac{C_L^{'}}{M} \; and \; C_D = \frac{C_D^{'}}{M} \; .$$

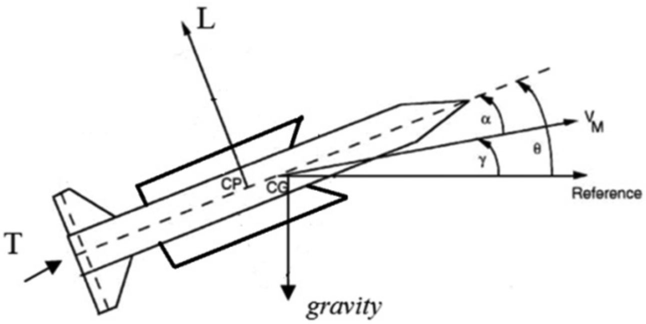

Figure 3. Diagram of the longitudinal Forces.

The thrust of the missile can be written as,

$$T = f(Ps, Ts, M, \alpha, \dot{m}_f) \qquad (10)$$

Using Taylor's Theorem, we get

$$\Delta T = \frac{\partial T}{\partial \dot{m}_f}.\Delta \dot{m}_f + \frac{\partial T}{\partial M}.\Delta M \qquad (11)$$

Substituting (4) and (11) in (9), we have

$$\Delta \dot{M} = \frac{A_{tr0}}{V_a m C_g}\frac{\partial T}{\partial \dot{m}_f}\Delta P_g + \frac{P_{go}}{V_a m C_g}\frac{\partial T}{\partial \dot{m}_f}\Delta A_{tr} + \frac{1}{mV_a}\left(\frac{\partial T}{\partial M} - \frac{\gamma}{2}P_s\left(C_D^{'}\cos\alpha - C_L^{'}\sin\alpha\right)\right)\Delta M \qquad (12)$$

Therefore, the state space model can be written as , $\dot{X} = AX + Bu$, where A and B matrices are as follows ,

$$\begin{bmatrix}\Delta \dot{P}_g \\ \Delta \dot{M}\end{bmatrix} = \begin{bmatrix}\frac{R_g T_g}{V_g}\left(\rho_g A_g \alpha P_{g0}^{n-1} - \frac{A_{tr0}}{C_g}\right) & 0 \\ \frac{A_{tr0}}{V_a m Cg}\frac{\partial T}{\partial \dot{m}_f} & \frac{1}{mV_a}\left(\frac{\partial T}{\partial M} - \frac{\gamma}{2}P_s\left(C_D^{'}\cos\alpha - C_L^{'}\sin\alpha\right)\right)\end{bmatrix} \begin{bmatrix}\Delta P_g \\ \Delta M\end{bmatrix} + \begin{bmatrix}-\frac{R_g T_g}{V_g}\frac{P_{g0}}{C_g} \\ \frac{P_{g0}}{V_a m C_g}\frac{\partial T}{\partial \dot{m}_f}\end{bmatrix}\Delta A_{tr} \qquad (13)$$

3. INTAKE CHARACTERISATION AND BUZZ MODELLING

In a mixed compression ramjet, the terminal shock position is determined by the intake back pressure, which is ideally equal to the combustion chamber pressure. In case of any disturbance in the combustion chamber pressure, it pushes the terminal shock outside the intake duct resulting in the un-start phenomenon which can be restarted without much problem. But if the combustion pressure is just sufficient that it pushes the terminal shock just at the cowl lip (Fig. 4) then a slight disturbance in the combustion chamber will push the shock just outside the intake duct and intake mass spillage will occur (*Dailey Criterion*) (Fig. 4). This occurs due to the boundary layer separation at the compression ramp.

As the shock moves upstream, the shear layer moves away from the cowl lip thus decreasing the intake air mass. So it'll force the shock to reattach itself to the cowl lip again. And again the high combustor pressure will push the shock just outside the intake duct, thus an oscillating phenomenon will occur. This phenomenon is termed as supersonic inlet buzz.

In general, intake design has been carried out to operate in critical zone with certain percentage of margin of back pressure for efficient operation. If, it is taken away by disturbance or uncertainties then through fuel flow controller it could be brought out in critical zone.

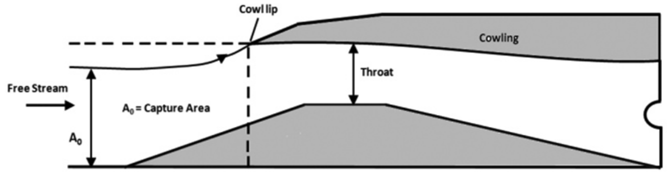

Figure 4. Schematic Diagram of the Intake Duct.

Hence, there is a need to control the terminal shock location in intake to operate intake back pressure within the margin

$$P_{margin} = \frac{P_{critical} - P_{operation}}{P_{critical} - P_{minimum}} \qquad (14)$$

Where, $P_{critical}$ and $P_{minimum}$ are the back pressure forward most limit and rear most limit of terminal shock location in intake duct.

P_{margin} is the back pressure operating band to maintain shock location within intake duct.

Once intake instability phenomena start, the control action is to be initiated to keep back pressure within the P_{margin} margin.

So, it is mandatory to characterize intake to all flight operating condition like Altitude, Mach no and alpha to calculate P_{margin} for fuel flow controller design. Data of intake back pressure as a function of Mach, Altitude and angle of attack have been evaluated through CFD or wind tunnel testing.

4. BUZZ MODELLING

The key to the dynamical model of intake is the updating of the combustion chamber/back pressure P_c based on the mass accumulation in the combustion chamber, i.e., the difference between the fuel plus air mass entering the combustion chamber and the gas mass exiting at the choked nozzle throat. This relation follows the work by Greitzer [1,11] for compression systems:

$$\dot{P}_c = \frac{1}{B_p}\left(\dot{m}_c - \dot{m}_{th}\right) \qquad (15)$$

Where, $\dot{m}_c$ is the mass of the fuel and air entering the combustion chamber , $\dot{m}_{th}$ is the mass of the air exiting from the exit nozzle throat and B_p is the back pressure factor given as ,

$$B_p = \int \frac{1}{\gamma R T(x)} A_{cch} \qquad (16)$$

Where, T(x) is the static temperature as a function of x which is the distance ranging from the fuel injection point to the exit nozzle throat and A_{cch} the area of the cross section of the combustor. B is constant for a given ramjet.

Using Mass conservation and assuming ideal conditions in between combustor exit and nozzle throat we can write,

$$\dot{m}_{th} = \frac{\beta A_{th} P_{oth}}{\sqrt{T_{oth}}} \qquad (17)$$

Where A_{th} is the throat area at the exit nozzle,

P_{oth} is the total pressure at the exit nozzle throat and T_{oth} is the total temperature at the exit nozzle throat and is a constant given by,

$$\beta = \sqrt{\frac{\gamma}{R}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (18)$$

T_{oth} is the maximum temperature at the combustor exit which is a constant value and in ideal conditions the static pressure at the throat is equal to the combustor pressure. Using isentropic relation, the total pressure at the exit nozzle throat (M = 1) is given by,

$$\frac{P_{th}}{P_{0th}} = \left(\frac{\gamma+1}{2}\right)^{\frac{-\gamma}{\gamma-1}} \tag{19}$$

Using (19) , we can rewrite (17) as ,

$$\dot{m}_{th} = \frac{\beta A_{th}}{\sqrt{T_{0th}}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} P_c \tag{20}$$

Now, for change in P_c equation (15) can be written as,

$$\Delta\dot{P}_c = \frac{1}{B}\left[(1+f)\Delta\dot{m}_a - \frac{\beta A_{th}}{\sqrt{T_{0th}}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}\Delta P_c\right] \tag{21}$$

Where f is the ratio of the fuel to the intake air mass and $\dot{m}_a$ is the intake air mass.

The difference between the combustion pressure and the intake pressure behind the terminal shock gives rise to the spillage in intake air mass. This can be formulated as,

$$\dot{m}_a = \frac{A_i}{L_i}\left(\Delta P_t - \Delta P_c\right) \tag{22}$$

Where A_i and L_i are the effective intake cross section area and length of the intake duct. P_t is the intake pressure behind the terminal shock.

The pressure behind the terminal shock is determined by the incoming Mach number and the free stream static pressure. Using the normal shock relation P_b can be written as,

$$P_t = P_\infty \frac{2\gamma M^2 - (\gamma-1)}{\gamma+1} \tag{23}$$

Using this relation change in the back pressure can be written as,

$$\Delta P_t = P_\infty \frac{4\gamma M}{\gamma+1}\Delta M \tag{24}$$

Using (23), equation (22) can be written as,

$$\Delta\dot{m}_a = \frac{A_i}{L_i}\left(P_\infty \frac{4\gamma M}{\gamma+1}\Delta M_t - \Delta P_c\right) \tag{25}$$

Combining (24) and (25) the equations can be written in matrix form as follows,

$$\begin{bmatrix}\Delta\dot{P}_c \\ \Delta\dot{m}_a\end{bmatrix} = \begin{bmatrix}\frac{\beta A_{th}}{B\sqrt{T_{0th}}}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} & \frac{1+f}{B} \\ -\frac{A_i}{L_i} & 0\end{bmatrix}\begin{bmatrix}\Delta P_c \\ \Delta\dot{m}_a\end{bmatrix} + \begin{bmatrix}0 \\ \frac{A_i}{L_i}P_\infty\frac{4\gamma M}{\gamma+1}\end{bmatrix}\Delta M \tag{26}$$

Here for an initial disturbance in the combustion chamber, the high pressure pushes the terminal shock wave outside the cowl lip which results in the spillage of the intake air mass. This spillage forces bring the shock wave to again reattach itself to the cowl lip and the high combustor pressure again pushes it out of the intake duct. Hence, this results an oscillating phenomena which is depicted in Fig. 5 and Fig. 6. If the fluctuating combustion/back pressure as shown in Fig. 5 could be damped out in first half cycle before crossing the back pressure margin. The buzz phenomena (instability) of intake can be avoided for smooth ramjet engine performance.

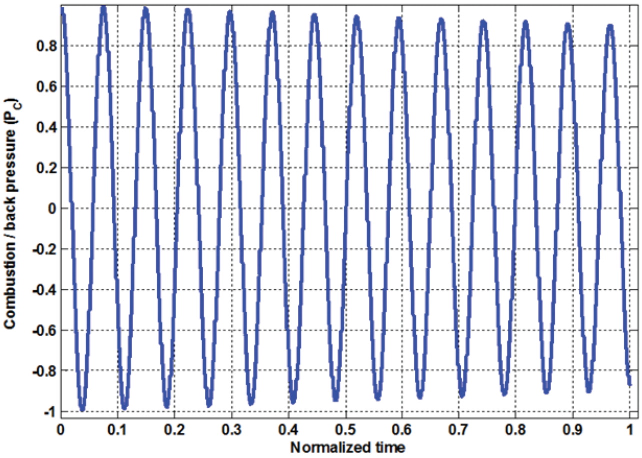

Figure 5. Buzzing effect of intake.

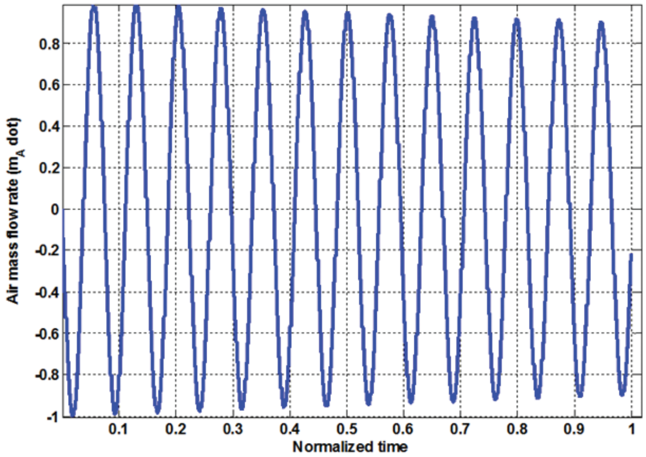

Figure 6. Buzzing effect on Air mass rate.

5. 3-LOOP STRUCTURE BASED FUEL FLOW CONTROL DESIGN

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[16]. It can be achieved by inverting the governing equations of the individual dynamics based on measured state and input command. The outer loop is the Thrust control loop and it has a slow dynamics characteristic. Inner loop is the pressure control loop and it has fast dynamics characteristic. Based on outer loop demand, the desired demand for fast loop can be computed. The main task of the controller is to track the commanded thrust and meet desire speed of response

In addition to the 2 loop FFC controller, a 3rd loop as a feed forward control is introduced as shown in Fig. 7 that controls the back pressure. The combustor pressure which is effectively

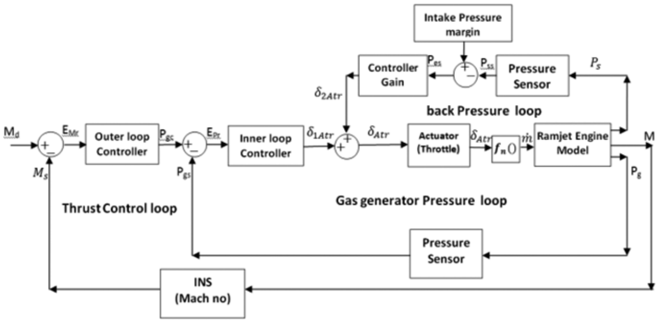

Figure 7. Representation of 3-loop Block diagram of FFC.

the back pressure is given by the chemical properties of the combustion process.

5.1 Outer Loop Design

The outer loop has the demanded Mach number which is available from the guidance loop which is to be attained by the FFC. The desired dynamics for the outer loop is given as,

$$\Delta\dot{M} = \omega_{outer}\left(\Delta M_d - \Delta M_s\right) \tag{27}$$

Where M_d and M_s stands for demanded and sensed Mach number respectively. And ω_{outer} is the time constant of outer loop. From the outer loop the demanded gas generator pressure can be computed from (12) as follows, neglecting the term of ΔA_{tr} as its value is much less than the other terms

$$\Delta P_{gc} = \frac{\Delta\dot{M} - \dfrac{1}{mV_a}\left(\dfrac{\partial T}{\partial M} - \dfrac{\gamma}{2}P_s\left(C_D^{'}\cos\alpha - C_L^{'}\sin\alpha\right)\right)\Delta M_s}{\dfrac{A_{tr0}}{V_a m C_g}\,\dfrac{\partial T}{\partial \dot{m}_f}} \tag{28}$$

5.2 Inner Loop Design

Gas generator pressure control loop receive the requirement from outer loop. The demanded throttle valve area can be computed from (7),

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

Where $\Delta\dot{P}_g = \omega_{inner}\left(\Delta P_{gc} - \Delta P_{gs}\right)$, P_{gc} and P_{gs} are the commanded and sensed gas generator pressure respectively and ω_{inner} is the time constant of the inner loop. This change in throttle valve area ensures the fuel flow rate

Such that the demanded thrust is achieved.

5.3 Back Pressure Loop Design

The back pressure loop receives the demanded margin by the user. The control logic is designed such that this loop gets triggered only when the pressure s out of the margin specified. When it is out of the margin specified then,

$$\Delta\dot{P}_c = \omega_{third}\left(\Delta P_{cc} - \Delta P_{cs}\right) \tag{30}$$

Where P_{cc} and P_{cs} are the demanded and sensed combustor pressure.

From the look up table available, the $\Delta\dot{m}_f$ is computed by linear interpolation and then it is integrated to get $\Delta\dot{m}_f$. From the computed value the requires throttle valve area is computed from (4)

$$\Delta A_{tr} = \frac{C_g}{P_{g0}}\left(\Delta\dot{m}_f - \frac{A_{tr0}\Delta P_{gc}}{C_g}\right) \tag{31}$$

This throttle valve area is passed to the plant.

If the back pressure is within the margin, then the throttle valve opening computed as mention in equation-29. The feed forward gain should be chosen as a function of the Mach number and altitude and other flight condition for a versatile performance over a wide range.

6. SIMULATION RESULTS ANALYSIS AND DISCUSSION

In this section, 2-loop dynamic inversion (DI) based fuel flow controller, feed forward based controller for back pressure as a third loop and engine plant modelling with intake dynamics are carried out in simulation environment in ideal condition (isotropic gas assumption).

Simulations have been carried out to show the performance of 3-loop based fuel flow controller for meeting the Mach no. demand in presence of disturbances. A typical Altitude and Mach no scenario has been chosen and applied a random disturbance in the combustion which is more prominent.

Simulation results of 3-loop structure-based controller, shown in Fig. 8 to Fig. 11, can be broadly analysed in three phase.

1. Phase-1 : Performance of ducted ramjet engine where Normalised time less than 0.4
2. Phase-2 : Performance at normalised time equal to 0.4
3. Phase-3 : Performance of ducted ramjet engine where Normalizes time greater than 0.4

Phase-1

To meet the Mach number demand, the 2-loop Fuel flow controller set the throttle valve area in a particular position so that required fuel mass rate can be injected from the gas

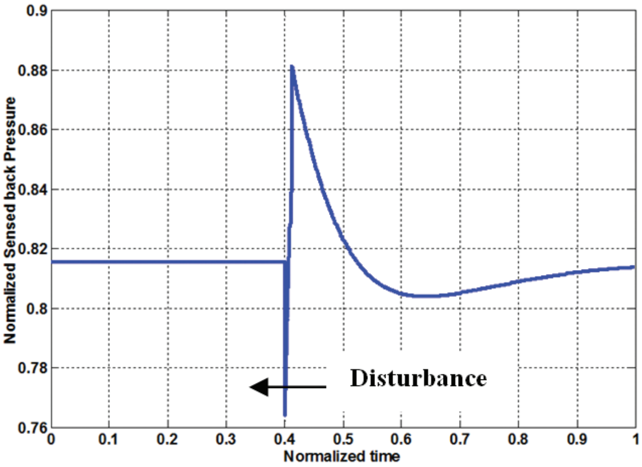

Figure 8. Back Pressure Variation due to disturbance.

generator to the combustion chamber. Injected Fuel mass rate gets mixed with air mass rate which enters through air-intake and burn to produce thrust. During this process, Pressure sensor keeps on sensing back pressure and back pressure margin is computed by 3-loop. If backpressure margin is within band, no action has been taken and it implies that terminal shock into the intake is in nominal location.

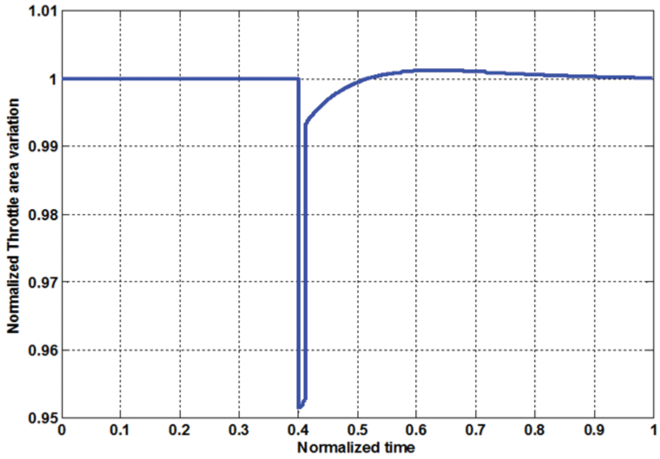

Figure 9. Throttle Area Variation.

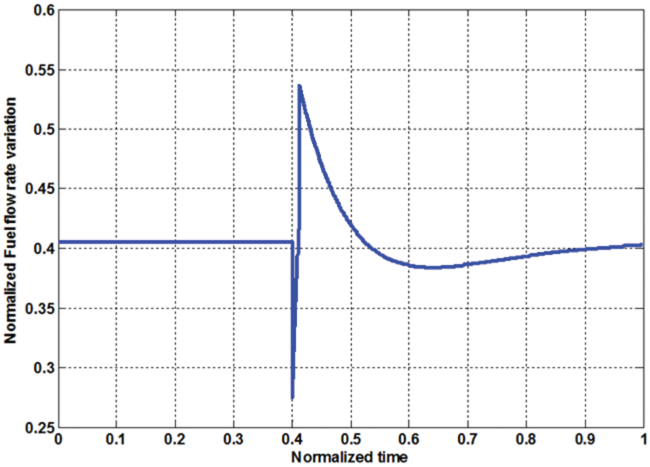

Figure 10. Fuel Flow Rate Variation.

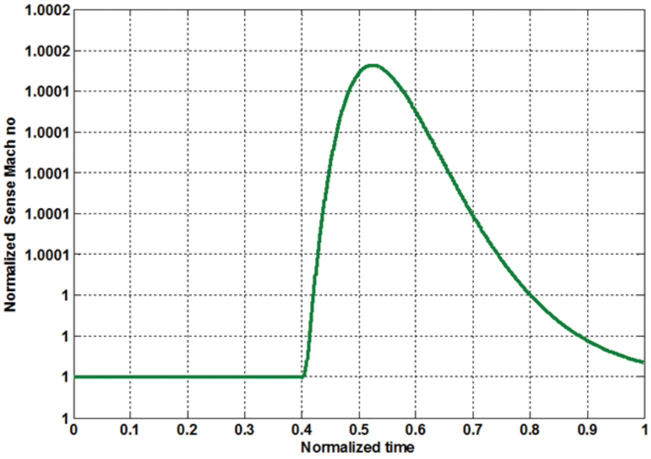

Figure 11. Mach number Variation.

Phase-2

Combustion pressure starts deviating due to disturbance. If it is not controlled, could lead to unstable intake phenomena like buzz which is shown in Fig. 5. Operation of engine has a detrimental effect due to it.

Phase-3

Once disturbance gets generated, the feed-forward loop gets activated before the disturbance digests all intake margins. Pmargin at given condition is computed and once it crosses the define value, feed-forward based back pressure loop start generating extra movement of throttle valve area to bring back margin in desire bound. Figure 9 show how fast the throttle valve area closes and the corresponding mass flow rate of gas generator vary to control the combustion pressure. During this process, the achieved thrust gets affected due to extra fuel flow rate variation which is injected in the combustion chamber. From the above results it is seen that the controller is successfully bringing down the Combustion chamber pressure / back pressure from the disturbance zone with minimum change in Mach number from the desired value.

7. CONCLUSIONS

(i) The main objectives of Fuel Flow Controller are to generate the desired thrust from combustion process to meet guidance requirement of air-to air/ surface to air tactical rocket.

(ii) Tactical based rocket have acute space constraint to put extra hardware for controlling pressure ratio margin of intake under disturbance.

(iii) A innovative provision without the use of hardware needs to protect pressure ratio margin within design margin of intake against the disturbances and ensure the ramjet engine performance.

(iv) This paper brought out the 3-loop structure based fuel flow controller design to control intake disturbances which effect the total ramjet engine performance.

(v) Feed forward based back pressure control loop need to act very fast to capture the fast dynamics of intake disturbances and it must be supported by a high bandwidth fuel flow actuator.

REFERENCES

1. Gretzer, E.M. Surge and Rotating Stall in Axial Flow Compressors- Part 1: Theoretical Compression System Model. *J. Eng. Power,* 1976, **98**, 90-198. doi: 10.1115/1.3446138
2. Thomaier, D. Speed control of ducted rocket with throttble ducted rocket propulsion. Advance in Air-launched weapon Guidance and contol, 1987, AGARD-CP-431.
3. Bauer, C.; Davenne, F.; Hopfe, N. & Kurthy, G. Modelling of a throttleable ducted rocket propulsion system. *In* Proc. AIAA/ASME/ASEE Joint Conference & Exhibit, california, 2011, pp. 1-15. doi: 10.2514/6.2011-5610
4. Bauer, C. & Kurth, G. Modelling of a TDR Propulsion System. *In* 47th AIAA/SME/SAE/ASEE Joint propulsion Conference and Exhibit, *AIAA*, San Diego. CA, July 2011.

5. Chandra, Kumar, P. B.; Nitin, K. Gupta; Ananthkrishanan, N. & Renganathan, V.S. Modeling, Dynamic Simulation and Controller Design For an Air-breathing Combustion System. *In* 47th AIAA Aerospace Sciences meeting, 5-8 January 2009, Orlando, Florida.
doi: 10.2514/6.2009-708
6. Juntao, Chang; Bin, Li.; Wen, Bao; Wenyu, Niu & Daren, Yu. Thrust control system design of ducted rockets. *Acta Astronautica,* 2011, **69**, 86-95, Elsevier.
doi: 10.106/J.actaastro.2011.02.010
7. Pedro, C. Pinto & Guido, Kurth. Robust Propulsion Control in all Flight stages of a Throtteable Ducted Rocket. *In* 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 31 July - 03 August 2011, San Diego, california.
doi: 10.2514/6.2011-5611
8. Anil, Alan; Yildiray, Yildiz; Poyraz, U. & Utku, Olgun. Gas Generator Pressure Control in Throttleable Ducted rockets : A Classical and adaptive control approach. *In* July 27-29, 2015, Orland, FL, 1st AIAA/SAE/ASEE Joint propulsion conference.
doi: 10.2514/6.2015-4236
9. Takayuki, kojima; Tetsuya, sato; Shujiro, S. & Nobuhiro, Tanantsuyu. Experimental study on restart control of a supersonic Air-breathing engine. *Journal of Propulsion and Power,* 2004, **20**(2).
doi: 10.2514/1.9253
10. Douglas, G. MacMartin. Dynamics and control of shock motion in a Near isentropic inlet. *Journal of Aircraft,* 2004, **41**(4).
doi: 10.2514/1.416
11. Simon, Trapier; sebastien, Deck; Philippe, Duveau & Pierre, sagant. Time-Frequency Analysis and Detection of Supersonic Inlet Buzz. *AIAA Journal,* 2007, **45**(9).
doi: 10.2514/1.29196
12. Bharani, chandra, kumar, P.; Nitin, K. Gupta & Ananthkrishna, N. Modeling Dynamic simulation and controller design for an Air-breathing combustion system. 47th AIAA Aerospace science meeting, 5-8 January, Orland, Florida.
doi: 10.2514/6.2009-708
13. IK-Soo, Park; Ananthkrishnan, N.; Min-Jea, Tahk; Vineeh, C.R. & Nitin, K. Gupta. Low-order model for Buzz oscillation in the intake of a ramjet engine. *Journal of Propulsion and Power*, 2011, **27**(2).
doi: 10.2514/1.50093
14. IK-Soo, Park; Sun-Kyoung, Kim; Hyo-Won, Yeon; Hong-Gye, Sung; Jung-Woo, Park & Min-Jea, Tahk. Control-oriented model for Intake shock position Dynamics in ramjet Engine. *Journal of Propulsion and Power,* 2011, **27**(2).
doi: 10.2514/1.53839
15. Tao, Cui; Young, Wang, Kai, Liu, & Jianren, Jin. Classification of Combustion-Inlet Interaction for Air-breathing ramjey Propulsion. *AIAA Journal,* 2015, **53**(8).
doi: 10.2514/1.J053378
16. Sriknt, srivastava; Dwivedi, P.N. & Vinod, kumar, D.M. 2-loop nonlinear dynamic inversion fuel flow controller design for air-to-air ducted ramjet rocket. *Def. Sci. J.,* 2021, **71**(2), 265-270,
doi: 10.14429/dsj.715165

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