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Variation of Fuel Consumption with PID Controller Tuning in Turbofan Engine System Using Simulation Approach

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Abstract- The study, variation of fuel consumption with PID controller tuning in turbofan engine system using simulation approach was successfully carried out. Two (2) dimensional turbofan engine system block model was created using simulink in MATLAB (R2015a).The model blocks were connected such that the PID has direct contact with engine system actuator and throttle position controller. Initial values of the system without tuning of PID controller were response time, proportional, integral, derivative, filter coefficient, frequency and phase angle corresponding to 0.7962 seconds 0, -1, 0, 100, 100rad/s and 0.5 degree respectively. Simulation was run for 10 seconds using Ode23t; as solver due to the need for high precision tolerance. The same simulation process was repeated with PID controller tuned with the response time, proportional, integral, derivative, filter coefficient, frequency and phase angle corresponding to 2 seconds 10, -2, 10, 100, 100rad/s and 0.5 degree respectively. Results showed that the time at which sharp changes occurred in fuel consumption of the engine system was found to be 5 seconds, within transient region. Fuel consumption at normal or un-tuned position of PID controller was found to 0.018 kg/s within response time of 0.7962 seconds of the engine system but decreases to minimum value of 0.005kg/s at the end of simulation time of 10 seconds. Similarly, Fuel consumption at tuned position of PID controller was found to 0.146 kg/s within response time of the engine operation but decreases to minimum value of 0.018kg/s with great stability at the end of simulation time of 10 seconds. The findings suggested the ability of PID controller tuning in decreasing and stabilizing both fuel consumption and propulsive thrust in a turbofan engine system.

Indexed Terms- PID tuning, fuel consumption, Simulation, Turbofan engine system

I. INTRODUCTION

Fuel (gas) is required as a thermal working fluid to drive turbofan engine system used for aircraft propulsion. The rate at which fuel is consumed in engine system, influence both thrust and engine economy. It has been the interest of the researchers to tailor all efforts towards achieving a sustainable fuel consumption rate (optimal level) that would give maximum thrust in turbofan engine drive system.

According to Ahmad (2020), as cited in Okoye et al (2023) maintained that turbofan is a gas turbine with combination of a mechanical ducted fan where both work together to achieve the thrust of the aircraft. The mechanical output of the gas turbine is partly used to drive the ducted fan.

NASA (2023) stated the economical fuel consumption to achieve a sustainable turbofan engine system operation as 0.5kg/hr/ thrust. But considering the scarcity of fuel gas and energy tussle enveloping the national economy of Nigeria, there is need to operate a turbofan engine system with fuel consumption below the NASA stated value while maintaining maximum thrust output.

Okoye et al (2023) carried out a study to determine the propulsive thrust and specific fuel consumption of a turbofan engine system using simulation method. Their study showed that at propulsive thrust 164N, specific fuel consumption of turbofan engine system was 0.06kg/s; they further added that mach number, throttle position, velocity of air and altitude are factors influencing turbofan engine thrust and fuel consumption. However, their study showed that thrust of turbofan engine increases with fuel consumption which might not be economically sustainable when higher thrust is needed.

Efosa et al (2023) examined that impact of PID controller on propulsive thrust and specific fuel consumption of a turbofan engine system using simulation method. The results from their study suggested PID connection could increase the propulsive thrust with increase in fuel consumption. The connection of PID controller to turbofan engine system increased the engine thrust from 310N to 470N with corresponding fuel increase from 0.098kg/s to 0.131 kg/s.

The current study proposed to utilize the tuning effect of PID controller to achieve increase in turbofan engine thrust with decrease in fuel consumption to make the system sustainable at higher thrusts values. It is on this note, the researchers aimed to study variation of fuel consumption with PID controller tuning in turbofan engine system using simulation approach.

The PID block in the simulink model adopted here is a continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the tune button.

II. METHODOLOGY

A 2 dimensional turbofan engine system simulink block model was created using MATLAB (R 2015a). The model blocks were connected such that the PID has direct contact with engine system actuator and throttle position controller. The fig 1.0, showed the components of the blocks and their respective connections. The simulation solver was Ode23t; this was chosen based on its high precision tolerance. Initial values of the system without tuning of PID controller were: response time = 0.7962seconds, proportional (P) = 0, integral (I) = -1, derivative (D) = 0 and filter coefficient (N) = 100, frequency = 100rad/s, phase angle = 0.5 degree.

Simulation was allowed to run for 10seconds and turbofan Engine System computed the fuel consumption of the overall system. The same process was repeated with PID controller tuned with the following conditions: response time = 2 seconds, proportional (P) = 10, integral (I) = -2, derivative (D) = 10 and filter coefficient (N) = 100, frequency = 100rad/s, phase angle = 0.5 degree. Simulation was run for 10 seconds both for normal and tuned conditions.

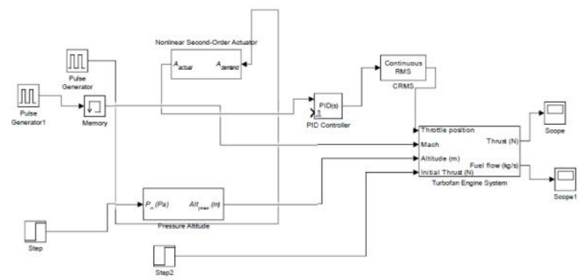

Fig 1.0: Adopted Simulink 2D Model

III. EQUATIONS

The formula below could be used to determine PID controller compensator

$Compensator = P + I\frac{1}{S} + D\frac{N}{1+N\frac{1}{S}}$ ….. (1.0)

The mathematical equations below could be adopted for calculating the propulsive thrust developed by turbofan engine system.

$Thrust = F = M_2V_2 - M_1V_1 \ldots\ldots\ldots\ldots\ldots\ldots.$ (2.0) (Okoye et al, 2023)

Where m and v are mass flow rate and velocity at exit (2) and inlet (1) of engine

The mass flow rate of fuel is given as below

$Mass\ flow\ of\ fuel = M_f = \rho_2V_2A_E - \rho_1V_1A_i \ldots\ldots\ldots\ldots\ldots\ldots.$ (3.0)

Where $A_E = exit\ area\ of\ fuel,$ $A_i = inlet\ area\ of\ fuel$

Thrust specific fuel consumption (TSFC) = $\frac{M_f}{F}$ ………… (4.0)

IV. RESULTS

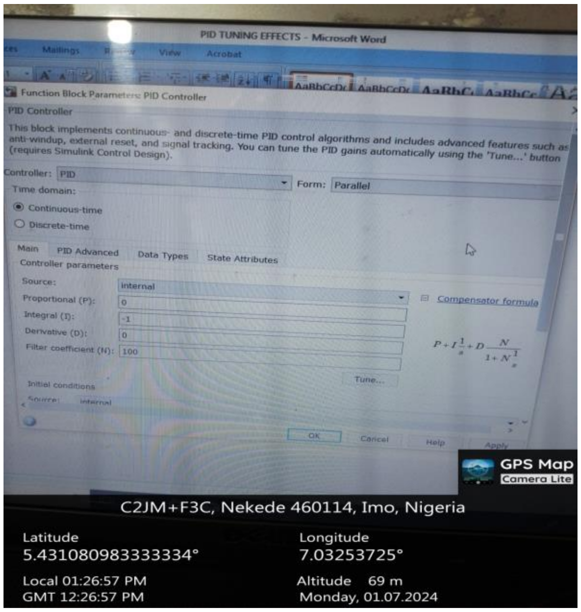

Fig 2.0: PID Controller Tuning in Normal Position

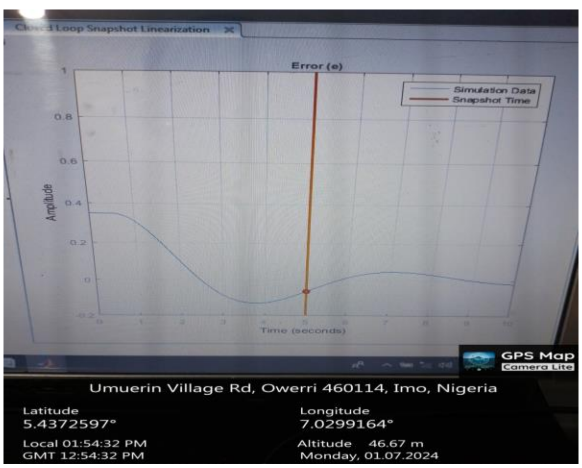

Fig 3.0: Snapshot Error and Time from Simulation Data

The fig 3.0 above showed the snapshot error and time from simulation data. This indicated the time at which sharp changes occurred in fuel consumption of the engine system. It was found to be 5 seconds, within transient region. This fig 3.0 also suggested that at 1 to 4 seconds, fuel consumption attained its lowest value but rises immediately after 5 seconds.

In addition, the following graphs below were obtained from simulation when initial values of the system without tuning of PID controller were: response time = 0.7962seconds, proportional (P) = 0, integral (I) = -1, derivative (D) = 0 and filter coefficient (N) = 100, frequency = 100rad/s, phase angle = 0.5 degree.

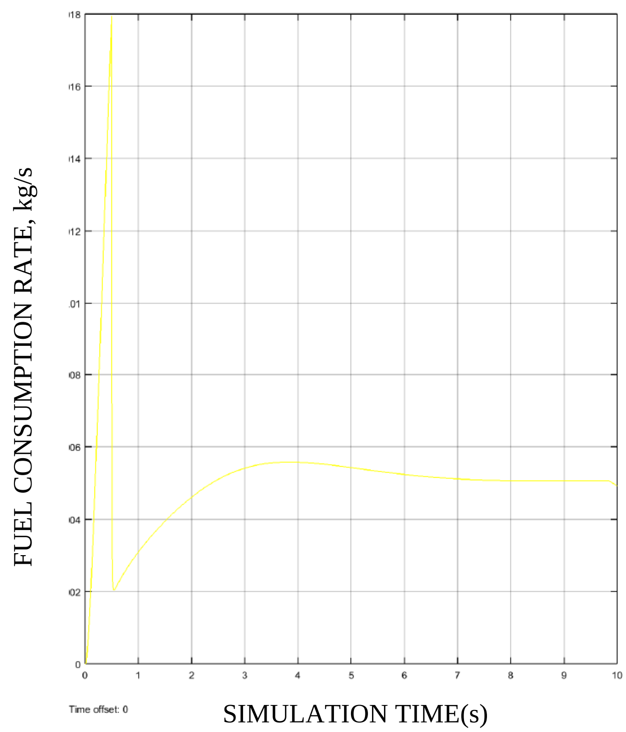

Fig 4.0: Graph of Fuel Consumption against Simulation Time

The graph of fuel consumption (fig 4.0) at the initial or normal values of PID controller showed that the maximum fuel consumption from the turbofan engine system was found to increase at a faster rate to 0.018kg/s, within 1 seconds of operation but decreases to 0.005kg/s as simulation time approaches 10 seconds. It was also to attain a maximum value of 0.0068kg/s within system response time of 0.7962 seconds. The PID controller influences the turbofan engine system to exhibit an aggressive response at the initial starting of the engine before transient state. The magnitude of sound from the engine system was found to be 1dB and also the amplitude of plant response was found to be equal with the amplitude of un-tuned response of PID controller which suggested proportionality relationship of operation time with fuel consumption.

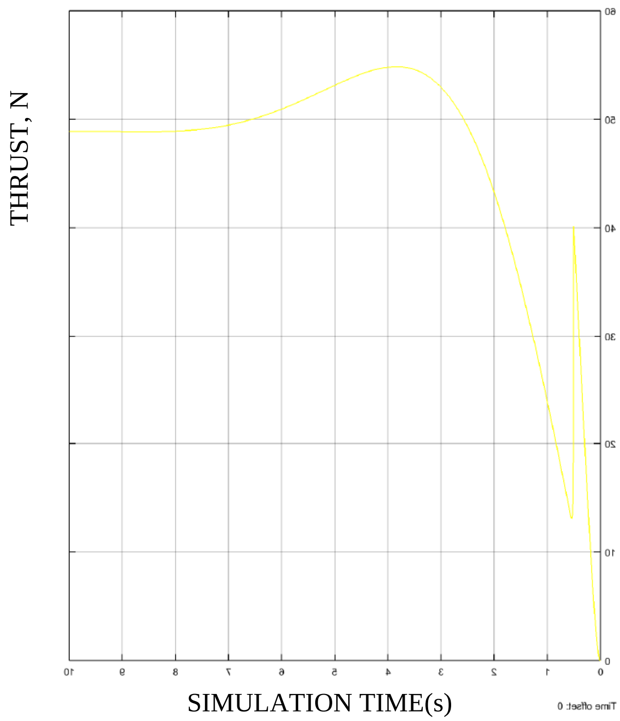

Fig 5.0: Graph of Thrust against Simulation Time

The graph of thrust with simulation time (fig 5.0) at the initial or normal values of PID controller showed that the maximum thrust from the turbofan engine system was found to increase at a faster rate to 400N, within 1 seconds of operation but increases to 475N as simulation time approaches 5 seconds and decreases below 450N as time approaches 10 seconds. This suggested that the connection of PID controller might increase turbofan engine system propulsion thrust. Decrease in value at the end of simulation time is a confirmation of linearity relationship with fuel consumption as claimed by Okoye et al (2023).

The following graphs below were obtained from simulation with PID controller tuned with the following conditions: response time = 2 seconds, proportional (P) = 10, integral (I) = -2, derivative (D) = 10 and filter coefficient (N) = 100, frequency = 100rad/s, phase angle = 0.5 degree.

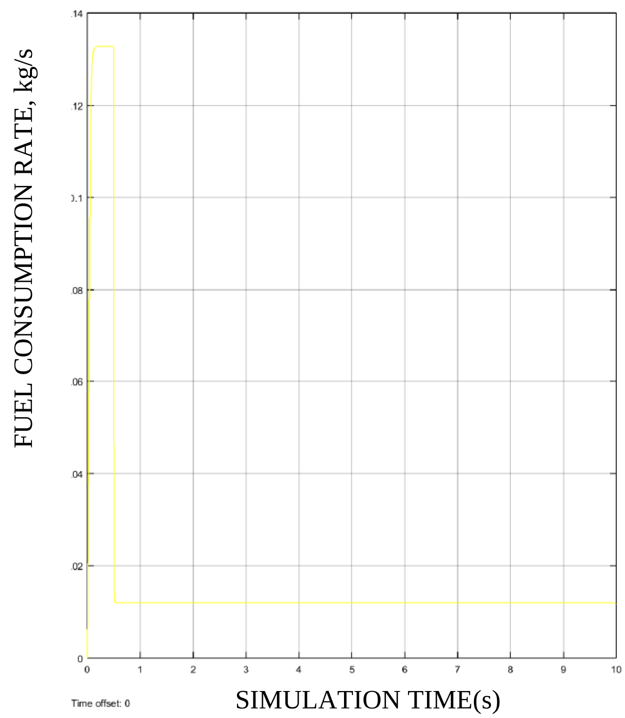

Fig 6.0: Graph of Fuel Consumption against Simulation Time in Tuned Condition

The graph of fuel consumption (fig 6.0) with simulation time at tuned condition of PID controller showed a sharp maximum rise in fuel consumption from the turbofan engine system from 0.146kg/s within 1 second of operation of engine and decreases within the same time limit to 0.018kg/s and finally levels off or maintained a stability at 0.018kg/s at the end of simulation. This result, suggested a decrease in fuel consumption with increasing engine thrust due to the stability tuning of PID controller offers the engine system.

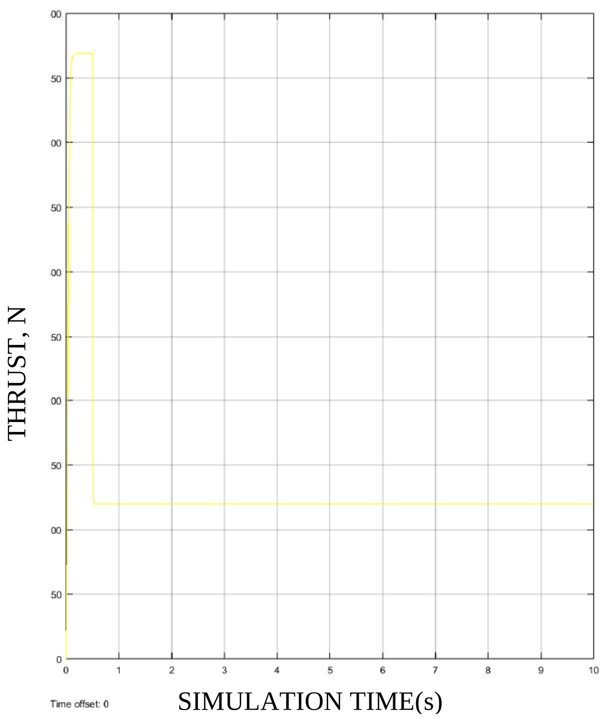

Fig 7.0: Graph of Thrust against Simulation Time in Tuned Condition

The graph of thrust (fig 7.0) with simulation time at tuned condition of PID controller showed a sharp maximum rise in thrust from the turbofan engine system from 475N within 1 second of operation of engine and decreases within the same time limit to 124N and finally levels off or maintained stability at 124N at the end of simulation. This result, suggested a rise and decrease in engine thrust but with great stability during full operation.

Table 1.0: Fuel Consumption and Thrust at Normal and Tuned Position

	FUEL CONSUMPTION AT NORMAL POSITION(kg/s)	FUEL CONSUMPTION AT TUNED POSITION(kg/s)	THRUST AT NORMAL POSITION(N)	THRUST AT TUNED POSITION (N)
Maximum value	0.018	0.146	400	475
Minimum	0.005	0.018	450	124
Value				

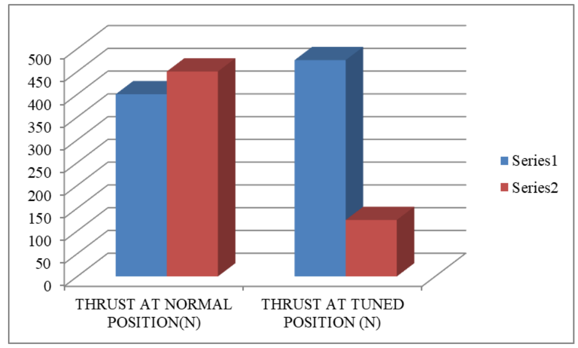

Fig 8.0: Bar Chart of Thrust against in normal and in Tuned Condition

SERIES 1 (Blue) = thrust at normal position Maximum and Minimum Values
SERIES 2 (Red) = thrust at tuned position Maximum and Minimum Values

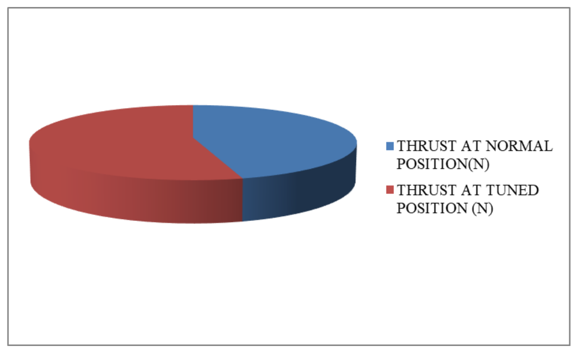

Fig 9.0: Pie Chart of Thrust against in normal and in Tuned Condition

SERIES 1 (Blue) = thrust at normal position Maximum and Minimum Values
SERIES 2 (Red) = thrust at tuned position Maximum and Minimum Values

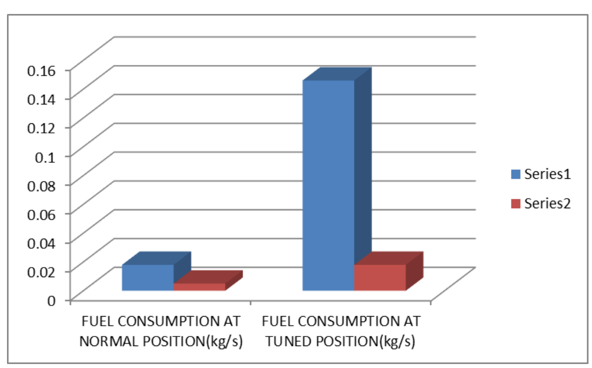

Fig 10.0: Bar Chart of Fuel Consumption against in normal and in Tuned Condition

SERIES 1 (Blue) = fuel consumption at tuned position Maximum and Minimum Values
SERIES 2 (Red) = fuel consumption at normal position Maximum and Minimum Values

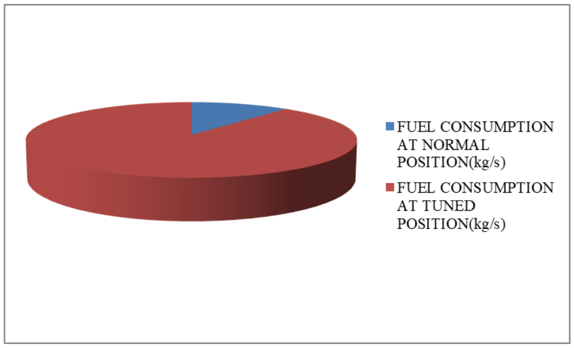

Fig 11.0: Bar Chart of Fuel Consumption against in normal and in Tuned Condition

SERIES 1 (Blue) = fuel consumption at normal position Maximum and Minimum Values
SERIES 2 (Red) = fuel consumption at tuned position Maximum and Minimum Values

CONCLUSION

Variation of fuel consumption with PID controller tuning in turbofan engine system using simulation approach was studied. The results from the study showed that the tuning of PID would increase fuel consumption at the starting of the engine which decreases as engine operation continued with great stability.

RECOMMENDATIONS

The following recommendations are suggested based on the study:

1) To minimize specific fuel consumption and achieve stability, PID controller should be tuned.
2) This research could also be done in future using different block design models, effective PID tuning and other advanced software for generalization.

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