



بسم الله الرحمن الرحيم

Sudan University of Science and Technology



STUDY THE EFFECT OF AUTOTHROTTLE ON FUEL CONSUMPTION RATE ON TURBOJET ENGINE USING MATLAB

Thesis submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science. (B.sc Honor)

In the

Department of Aeronautical Engineering

Faculty of Engineering

By:

1. Mohamed Omer Abd AL Hameed Ali.
2. Rana Izzeldin Babekir Ibrahim.

Supervised By:

Ms. Raheeg Osama wahbi Alamin

October, 2015

الآية

قال تعالى :

﴿ أَلَمْ يَرَوْا إِلَى الطَّيْرِ مُسَخَّرَاتٍ فِي جَوِّ السَّمَاءِ مَا يُمْسِكُهُنَّ
إِلَّا اللَّهُ إِنَّ فِي ذَلِكَ لَآيَاتٍ لِّقَوْمٍ يُؤْمِنُونَ ﴾

سورة النحل. الآية (79)

Abstract

Autothrottle (automatic throttle) is a system that automatically manipulates the thrust setting of an aircraft's engines. Used to reduce pilot workload, fuel consumption and also reduce unwanted throttle motion. This thesis is a report on a study of the effect of the autothrottle system on fuel consumption rate in jet engines. There are two modes when implementing autothrottle either engine pressure ratio (EPR) or speed mode. This thesis concentrates on the response of the fuel valve to throttle angle (θ). Block diagram proposed to design a closed loop system single input single output (SISO) to represent an autothrottle using throttle angle (θ) as input and engine R.P.M as output as main variable that will affect the other engine and aircraft variables and forces. MATLAB code had been used to plot system response for different design stages and cases. The combination of PID controllers studied regarding the best performance characteristics (t_r , t_s , overshoot) to select the best performance and fastest response. Simulation results supported the theory of the relation between autothrottle, airspeed, engine RPM and fuel consumption rate. Estimating the variables for servo and controllers due to lack of data, results in deviation on some readings, that can be solved by working with real engine. Turbofan is suggested for less fuel consumption and adaptive controller is suggested as well.

Acknowledgment

Verily all praise is for Allah, we praise him, seek his help and guidance.

We are deeply grateful to many. To our supervisor **Raheeg Alamin**, and another special thanks to **Dr. Osman Emam** for his guidance and support all through this year.

To **Mohamed Taha** for his great help and concern.

To **Support Team**/ fourth year Aeronautical Department Batch 15.

To our **parents** and **family**, whose support is abundant, and whose love is nourishing.

Our **colleagues**, we express appreciation for creativity, discipline, competence and friendship.

Symbols

K	Gain
θ	The throttle position
V_i	Input speed
V_o	Output speed
V_{S0}	Stall speed in the landing configuration
T	Thrust
t_d	Delay time
t_r	Rise time
t_s	Settling time
M_p	Maximum overshoot
t_p	Peak time

Abbreviation

ATC	Air traffic control
ECU	Engine Control Unit
EPR	Engine pressure ratio
FADEC	Full authority digital engine control
FMC	Flight management computer
HMU	Hydro-mechanical Unit
MCP	Mode control panel
MIMO	Multi input multi output
SISO	Single input single output
TQA	Throttle Quadrant Assembly
TECS	Total energy control system
TMC	Thrust management computer

Contents

الآية	i
Abstract	ii
Acknowledgment	iii
Symbols.....	iv
Abbreviation	v
Contents	vi
Table of Figures	ix
List of Tables	x
Chapter 1: Introduction	1
1.1 Overview	1
1.2 Aim and objectives	1
1.2.1 Aim.....	1
1.2.2 Objectives.....	1
1.3 Problem Statement.....	2
1.4 Proposed Solution.....	2
1.5 Motivation	2
1.6 Contribution.....	3
1.7 Methodology.....	3
1.8 Outline	3
Chapter 2: Literature Review	5
2.1 Engine Types and Applications	5
2.1.1 Turbo Jet Engine	6
2.1.2 Turbofan Engine.....	6
2.1.3 Turbo-shaft Engine.....	7
2.1.4 Turbo-prop Engine	7

2.2 Jet Engine Theory.....	8
2.2.1 Principle of Operation	8
2.3 Jet Engine Equation	9
2.4 Factors Affecting Thrust.....	9
2.5 Summary.....	10
Chapter 3: Aircraft Fuel System	11
3.1 Fuel System General Requirement.....	11
3.2 Fuel Flow Rate	12
3.3 Aircraft Engine Control Concept	14
3.4 Control Theory	15
3.4.1 Classical Control Theory	15
3.4.2 Modern Control Theory	16
3.4.3 Optimal Control Theory.....	16
3.5 Control Design Objectives	16
3.6 Types of Controllers.....	17
3.6.1 Proportional Controllers.....	17
3.6.2 Integral Controllers	18
3.6.3 Derivative Controllers.....	18
3.6.4 PID Controller.....	19
3.6.5 Proportional and Integral Controller.....	20
3.6.6 Proportional and Derivative Controller	20
3.7 Full Authority Digital Engine Control (FADEC)	23
3.7.1 FADEC Components	23
Chapter 4: Autothrottle system	24
4.1 Background and Operation.....	24
4.1.1 Operation.....	26
4.2 Air Traffic Control.....	28

4.3 Autothrottle System Design.....	29
4.4 Summary	30
Chapter 5: Simulation of Autothrottle using MATLAB.....	31
5.1 Relation between Thrust, Aircraft Speed and Engine RPM.....	31
5.2 Results	34
5.2.2 PID Tool.....	35
Chapter 6: Conclusion and Recommendation.....	40
6.1 Conclusion.....	40
6.2 Future work	40
Appendix.....	42

Table of Figures

Figure 1: Turbo Jet Engine Sections	6
Figure 2: Turbofan Engine Sections	6
Figure 3: Turbo-Shaft Engine Sections.....	7
Figure 4: Turbo-Prop Engine Sections	7
Figure 5: Maximum Thrust (lbs) at each Altitude.	14
Figure 6: PID Controller Block Diagram.....	21
Figure 7: Transient and Steady-State Response Analyses source [9].....	22
Figure 8: FADEC Control Philosophy.....	23
Figure 9: Autothrottle Unit	26
Figure 10: Block Diagram of Typical Modern Engine Control Logic (image courtesy of NASA). Source [4].....	27
Figure 11: Proposed Block Diagram by <i>Rebecca</i>	29
Figure 12: Simplified Proposed Block Diagram for Auto-throttle	31
Figure 13: Root Locus	32
Figure 14: Sub system, throttle command	33
Figure 15: Open Loop Step Response	34

List of Tables

Table 1: Effects of each of controller K_p , K_d , and K_i on a closed-loop system	21
Table 2: Basic Auto throttle Functions over the Flight Profile.....	25
Table 3: Variables Table	32

Chapter 1: Introduction

1.1 Overview

Aircraft engine performance parameters, such as thrust, provide crucial information for operating an aircraft engine in a safe and efficient manner, but they cannot be directly measured during flight. A technique to accurately estimate these parameters is, therefore, essential for further enhancement and control of engine operation.

The basic engine control concept is to provide smooth, stable, and stall free operation of the engine via single input with no throttle restrictions and to have a reliable and predictable throttle movement to thrust response.

A primitive auto throttle was first fitted to later versions of the Messerschmitt Me 262 jet fighter late in World War II. Today it is often linked to a Flight Management System, and FADEC is an extension of the concept to control many other parameters besides fuel flow.

An autothrottle (automatic throttle) control the power setting of an aircraft's engines by specifying a desired flight characteristic, rather than manually controlling the fuel flow. These systems can conserve fuel and extend engine life by metering the precise amount of fuel required to attain a specific target indicated air speed, or the assigned power for different phases of flight.

1.2 Aim and objectives

1.2.1 Aim

To study the effect of autothrottle on reducing pilot workload and fuel consumption, what claimed to increase the range of the aircraft and reduce flight cost, by design and control a simple autothrottle.

1.2.2 Objectives

Study how autothrottle control the speed of the aircraft by adjusting the position of the throttles and ensures that the maximum fuel efficiency is obtained by the engines during all stages of flight, by:

- Study the theory of throttling system.

- Propose a simple loop for design using engine RPM instead of aircraft airspeed.
- Make the throttle work automatically.
- Build a control loop. Using PID controller and MATLAB
- Analyse the responses in relation to theory.

1.3 Problem Statement

Due to the increase of the demand for using aircraft as a safe and practical transportation media for the growing business worldwide, it becomes very important to start looking for improving their engine's performance in terms of fuel consumption. Thus there will be efficient, reliable, competent and cost effective means of transportation to play the main role in the business world. Even small changes in aircraft performance and fuel efficiency can have a cumulative large impact on operating costs. So in improving the aircraft engine performance, fuel consumption should be considered as the main factor of improvement.

1.4 Proposed Solution

Applying a PID controller to simple autothrottle closed loop circuit using throttle angle (θ) as input and engine R.P.M as output, in order to improve and to accelerate throttle valve response to optimize the fuel consumption.

1.5 Motivation

The engine performance stability is a main thing to look for to decide if the controller implemented to it is good enough to operate. We need the aircraft engine to deliver forward/reverse and positive/negative torque to drag the control surfaces after moving the throttle with seamless fuel losses. Quality control imposes further requirements for stable system, smooth torque, fast dynamic response, and ability to operate at zero speed.[1]

The great challenge is come with taking variables as functions on others when dealing with aircraft engines.

To consider as good operation for the autothrottle system the response should be fast and smooth (minimum settling and rise time) with minimum overshoot. Controlling the throttle is depends on the engine pressure or aircraft speed which is a

function of engine rpm. These constraints have to be managed very tightly in order to implement autothrottle in aircraft especially during take-off and landing.

1.6 Contribution

This project is a great chance to apply most of the theories about the aircraft engine controlling by taking the throttle system and control it by building a control loop and simulate it by using MATLAB. Aircraft engine rpm had been chosen to be the controlling variable, all other variables, inputs and outputs from the system is been connected to the engine rpm. The objective of the project is to make the throttle system run under the software control then study its effect of the fuel consumption rate will be fulfilled by designing and simulating the control loop circuit including the indication of (throttle angle Θ) and rpm.

1.7 Methodology

Simulation and analytical methodology have been used to go through this study. From previous research it was clear that it is not easy to design a control law for a throttle system, that's why simulation was the best way to go with. RPM of the engine was related to the thrust, speed fuel flow rate, then represented as the output of the proposed block diagram while throttle angle was the input. MATLAB with M file and PID tool used to simulate the system and discussion made regarding the response characteristics.

1.8 Outline

The thesis is organised as follow:

Chapter one as a general introduction about the aircraft engine: its history and applications. The inherent control problems rising with the fuel flow and thrust are briefly discussed. Then the objectives of the project, the motivation and contribution of this thesis are given.

In Chapter two, the principle of the thrust is discussed from both a physical and mathematical point of view. The controlling problem and some researches discussed briefly in this chapter.

Chapter three, for detailed study in the control issues with auto throttle and looks at the speed and thrust as the modes to be controlled this done by choosing the fuel flow rate to be observed and the speed to sensed and controlled by a feedback system.

The preparation for the project and things that needed to set all placed by their calculation and specification in brief in the fourth chapter.

All the graphs to be needed to monitor the engine and the result are captured and putted with a detailed discussion in chapter five.

Chapter six concluded the entire project and proposes for further research, then the appendices.

Chapter 2: Literature Review

Aircraft jet turbine engine were used at the end of World War II. Before that, engines were piston has identified the aircraft speed were replaced by turbine engines, which was the most efficient and all the faces compared with these engines where it was possible to get the momentum and thrust of the largest of turbo engines, the mass of relatively less engine and the qualitative (the engine percentage-dimensional volumetric to the thrust power of that engine) for at least several times that figure at best piston engines. As well as increased dramatically aircraft turbine engines which were used jet speed, reaching the speed of the aircraft for the first generation of turbo-engines to the limit (950 km / h), while aircraft piston engines speed did not exceed (750 km / h).

After that many types of jet turbine engines appeared and those types can be divided into two groups (turbo jet engines, turbo prop engines). And between these two groups there are (turbo fan or By-pass engines) such as these engines to get take-off and flight highs speeds outweigh significantly the speed of sound, high efficiency and a relatively large flight range.[2]

2.1 Engine Types and Applications

Most of modern passenger and military aircraft are powered by gas turbine engines, which are also called jet engines. There are several types of jet engines, but all jet engines have some parts in common.

Aircraft gas turbine engines can be classified according to the type of compressor used or power produced by the engine.

Compressor types are as follow:

1. Centrifugal flow.
2. Axial flow.
3. Centrifugal-Axial flow.

Power produced is as follow:

1. Turbojet engines.
2. Turbofan engines.
3. Turbo-shaft engines.
4. Turboprop engines.
5. Piston engine.

2.1.1 Turbo Jet Engine

Turbojet engine derives its thrust by highly accelerating a mass of air, all of which goes through the engine. Since a high “jet” velocity is required to obtain an acceptable of thrust, the turbine of turbojet is designed to extract only enough power from the hot gas stream to drive the compressor and accessories. All of the propulsive force (100% of thrust) produced by a jet engine derived from exhaust gas.

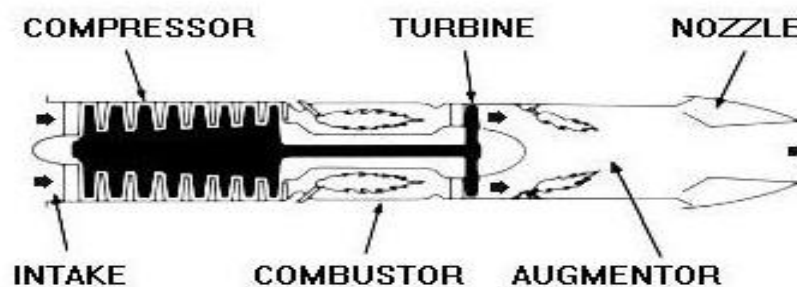


Figure 1: Turbo Jet Engine Sections

2.1.2 Turbofan Engine

Turbofan engine has a duct enclosed fan mounted at the front of the engine and driven either mechanically at the same speed as the compressor, or by an independent turbine located to the rear of the compressor drive turbine. The fan air can exit separately from the primary engine air, or it can be ducted back to mix with the primary's air at the rear. Approximately more than 75% than thrust comes from fan and less than 25% comes from exhaust gas.[3]

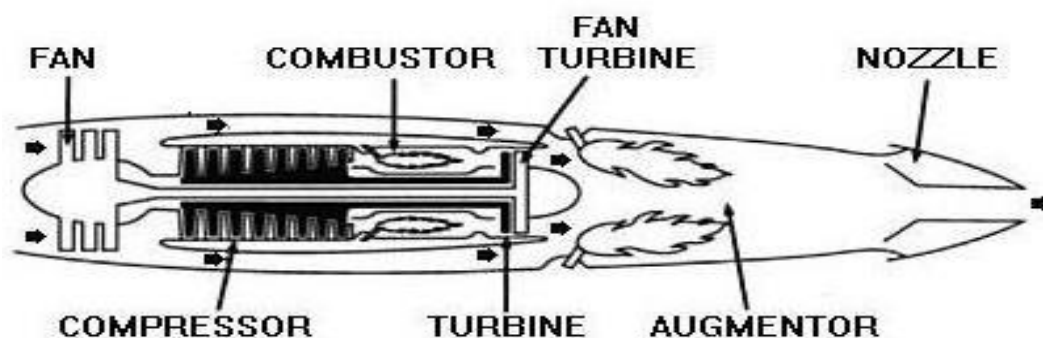


Figure 2: Turbofan Engine Sections

2.1.3 Turbo-shaft Engine

Turbo-shaft engines derives its propulsion by the conversion of the majority of gas stream energy into mechanical power to drive the compressor, accessories, just like the turboprop engine but the shaft on which the turbine is mounted drives something other than an aircraft propeller such as the rotor of a helicopter through the reduction gearbox.[3]

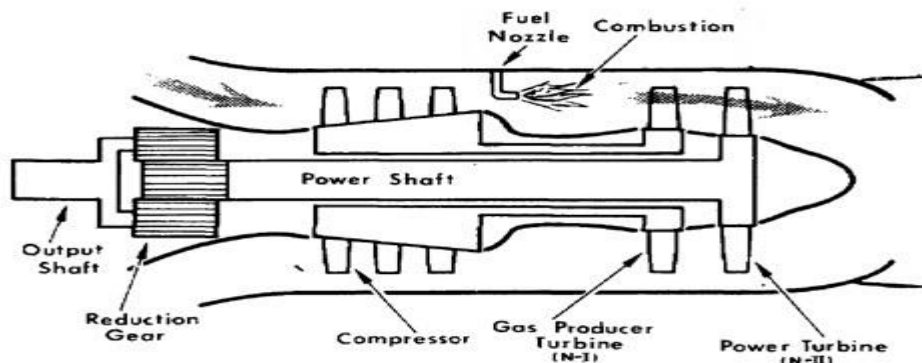


Figure 3: Turbo-Shaft Engine Sections

2.1.4 Turbo-prop Engine

Turboprop engine derives its propulsion by the conversion of the majority of gas stream energy into mechanical power to derive the compressor, accessories, and the propeller load. The shaft on which the turbine is mounted drives the propeller through the propeller reduction gear system. Approximately 90% of thrust comes from propeller and about only 10% comes from exhaust gas.[3]

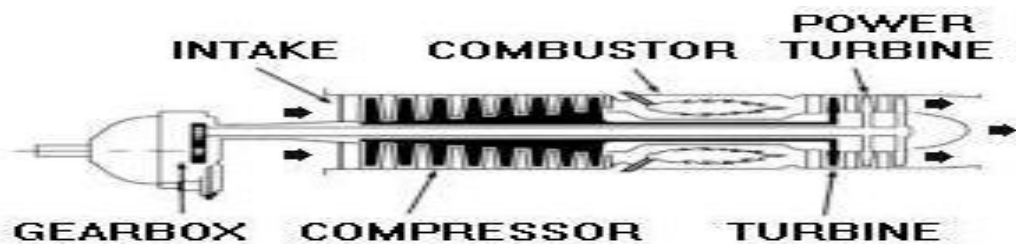


Figure 4: Turbo-Prop Engine Sections

2.2 Jet Engine Theory

2.2.1 Principle of Operation

The jet engines are essentially a machine designed for the purpose of producing high velocity gasses at the jet nozzle. The engine is started by rotating the compressor with the starter, the outside air enters to the engine. The compressor works on this incoming air and delivery it to the combustion or burner section with as much as 12 times or more pressure the air had at the front. At the burner or combustion section, the ignition is igniting the mixture of fuel and air in the combustion chamber with one or more ignites which somewhat likes automobile spark plugs. When the engine has started and its compressor is rotating at sufficient speed, the starter and ignites are turn off. The engine will then run without further assistance as long as fuel and air in the proper proportions continue to enter the combustion chamber. Only 25% of the air is taking part in the actual combustion process. The rest of the air is mixed with the products of combustion for cooling before the gases enter the turbine wheel. The turbine extracts a major portion of energy in the gas stream and uses this energy to turn the compressor and accessories. The engine's thrust comes from taking a large mass of air in at the front and expelling it at a much higher speed than it had when it entered the compressor. **THRUST, THEN, IS EQUAL TO MASS FLOW RATE TIMES CHANGE IN VELOCITY.**

$$\mathbf{F = ma = (v_j - v_0) = mv_j - mv_0..... (2.1)}$$

Where:

F = Thrust in lbs.

M= mass flow rate of air ibs/sec.

v_0 = Incoming air velocity ft/sec.

v_j = Exhaust gas velocity ft/sec.

The more air that an engine can compress and use, the greater is the power or thrust that it can produce. Roughly 75% of the power generated inside a jet engine is used to drive the compressor. Only what is left over is available to produce the thrust needed to propel the airplane.[3]

2.3 Jet Engine Equation

Since Fuel flow adds some mass to the air flowing through the engine, this must be added to the basic of thrust equation. Some formula does not consider the fuel flow effect when computing thrust because the weight of air leakage is approximately equal to the weight of fuel added. The following formula is applied when a nozzle of engine is "choked", the pressure is such that the gases are travelling through it at the speed of sound and cannot be further accelerated. Any increase in internal engine pressure will pass out through the nozzle still in the form of pressure. Even this pressure energy cannot turn into velocity energy but it is not lost.

$$F_n = (mv_j + mv_0) + m_f v_j + A_j(P_j + P_{am}) \dots \dots \dots (2.2)$$

Where:

F_n = Net thrust in lbs

m = Mass flow rate of air lbs/sec.

v_0 = Incoming air velocity ft/sec.

v_j = Exhaust gas velocity ft/sec.

m_f = Fuel mass flow rate lbs/sec.

A_j = Area of engine jet nozzle sq-in.

P_j = Static pressure at jet nozzle lbs/sq-in

P_m = Static ambient pressure at exhaust nozzle lbs/sq-in

2.4 Factors Affecting Thrust

The Jet engine is much more sensitive to operating variables. Those are:

1. Engine rpm.
2. Size of nozzle area.
3. Weight of fuel flow.
4. Amount of air bled from the compressor.
5. Turbine inlet temperature.
6. Speed of aircraft (ram pressure rise).
7. Temperature of the air.
8. Pressure of air.
9. Amount of humidity.

Most of the factors all highly dependent on the engine, especially the fuel flow rate. Thus to control the aircraft engine in general the fuel is what we should look at.

2.5 Summary

This chapter introduced the main idea and information about the aircraft engine, jet engine theory and the factors affecting thrust.

Chapter 3: Aircraft Fuel System

The aircraft fuel system serves for storing the required amount of fuel used by engines operation under all flight conditions. The purpose of an aircraft fuel system is to store and deliver the proper amount of clean fuel at the correct pressure to the engine. Also fuel systems should provide positive and reliable fuel flow through all phases of flight including:

1. Changes in altitude.
2. Violent manoeuvres.
3. Sudden acceleration and deceleration.

The fuel system is one of the more complex aspects of the gas turbine engine. The variety of methods used to meet turbine engine fuel requirements makes reciprocating engine carburetion seem a simple study by comparison.

Turbine-powered aircraft this control is provided by varying the flow of fuel to the combustion chambers. However, turboprop aircraft also use variable-pitch propellers; thus, the selection of thrust is shared by two controllable variables, fuel flow and propeller blade angle. If the quantity of fuel becomes excessive in relation to mass air flow through the engine, the limiting temperature of the turbine blades can be exceeded, or it will produce compressor stall and a condition referred to as "rich blowout".

3.1 Fuel System General Requirement

1. It must be possible to increase or decrease the power at will to obtain the thrust required for any operating condition.
2. The quantity of fuel supplied must be adjusted automatically to correct for changes in ambient temperature or pressure.
3. The fuel system must deliver fuel to the combustion chamber not only in the right quantity but also in the right condition to satisfactory combustion.
4. The fuel system must also supply fuel so that the engine can be easily started on the ground and in the air. This means that the fuel must be injected into the combustion chamber in a combustible condition when the engine is being turned

over slowly by the starting system and the combustion must be sustained while the engine is accelerating to its normal running speed.

5. A critical condition to which the fuel system must be respond occurs during slam acceleration. When the engine is accelerated, energy must be furnished to the turbine in excess of that necessary to maintain a constant rpm. However, if the fuel flow increases too rapidly, an over rich mixture can be produced, with the possibility of a rich blowout.[3]

3.2 Fuel Flow Rate

The ability of the fuel system to provide fuel at a rate of flow and pressure sufficient for proper engine operation is vital in aircraft. Moreover, the fuel system must deliver the fuel at the aircraft attitude that is most critical with respect to fuel feed and quantity of unusable fuel. Tests are performed to demonstrate this performance. Fuel flow-meters are installed on most aircraft. During testing, the flow-meter is blocked and fuel must flow through or bypass the meter and still supply the engine at sufficient rate and pressure. For gravity-flow fuel systems, the fuel flow rate must be 150 percent of the take-off fuel consumption of the engine. For fuel pump systems, the fuel flow rate for each pump system (main and reserve supply) for each reciprocating engine must be 125 percent of the fuel flow required by the engine at the maximum take-off power. However, the fuel pressure, with main and emergency pumps operating simultaneously, must not exceed the fuel inlet pressure limits of the engine. Auxiliary fuel systems and fuel transfer systems may operate under slightly different parameters. Turbine engine fuel systems must provide at least 100 percent required by the engine under each intended operating condition and manoeuvre. On aircraft with multiple fuel tanks, performance is monitored when switching to a new tank once fuel has been depleted from a tank. For reciprocating, naturally aspirated, single-engine aircraft in level flight, 75 percent maximum continuous power must be obtainable in not more than 10seconds. For turbocharged aircraft, 20 seconds is allowed. Twenty seconds is also allowed on multiengine aircraft flow between Interconnected Tanks.

In gravity feed fuel system with interconnected tank outlets, it must be impossible for enough fuel to flow between the tanks to cause an overflow of fuel from any tank vent

under the conditions in 14 CFR parts 23, section 23.959. If fuel can be pumped from one tank to another in flight, the fuel tank vents and the fuel transfer system must be designed so that no structural damage to any airplane component can occur because of overfilling of any tank.

$$\dot{m}_{ac} = -\dot{m}_f \dots\dots\dots (3.1)$$

$$\dot{m}_f = \dot{m}_T \cdot F_T \dots\dots\dots (3.2)$$

Where:

$\dot{m}_{ac}$ = Change of mass of the aircraft.

$\dot{m}_f$ = Fuel mass flow rate.

T = Thrust.

F = force.

According to previous research altitude increasing leads to thrust decreasing. This decrease in thrust is shown in Figure [5] below. By taking in account the consideration average throttle lever angle; At low thrust settings the engine takes longer to respond to thrust settings, so to help prevent excessive movement, lower gains are used at low throttle angles. Another compensation that is used in this control law is pitch angle. While tracking altitude, the pitch angle is not used because the changes in pitch angle are small. However, during other phases of flight, initial changes in pitch angle should be accounted for when controlling speed, because the angle of the force of thrust is changing. Once an initial compensation for pitch angle has been added, it is washed out, so pitch angle does not create an unnecessary long term bias in the command. Thrust in different altitude is shown in figure [5] below for the case of study.

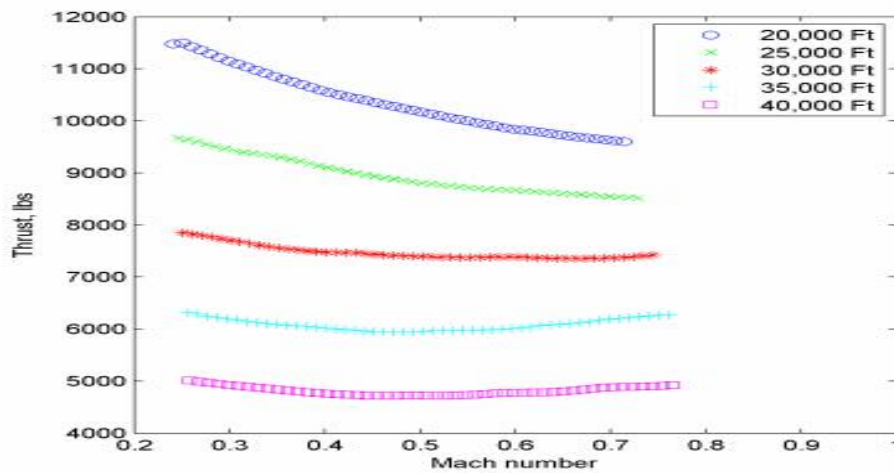


Figure 5: Maximum Thrust (lbs) at each Altitude.

It is not always available for study, that's why we need to use simple controllers and represent the system components by the dynamic using orders and reduced orders.

3.3 Aircraft Engine Control Concept

To avoid many problems because thrust cannot be measured and the changes in ambient condition and aircraft manoeuvres cause distortion into the fan/compressor need to be controlled. Also need to protect the engine in harsh operating environment high temperatures and large vibrations which in such environment the engine need a safe operation to avoid stall, combustor blow out. Another reason that to provide long operating life (20,000 hours) because engine components degrade with usage need to have reliable performance throughout the operating life since Thrust (T) cannot be measured, use fuel flow to control shaft speed, or other measured variable that correlates with thrust:

$$T = F(N) \dots\dots\dots (3.3)$$

Limits are implemented by limiting fuel flow based on rotor speed. The maximum fuel limit protects against surge/stall, over-temp, over speed and over-pressure and the minimum fuel limit protects against combustor blowout. The actual limit values are generated through simulation and analytical studies.[4]

3.4 Control Theory

Is an interdisciplinary branch of engineering and mathematics that deals with the behaviour of dynamical systems with inputs, and how their behaviour is modified by feedback. The usual objective of control theory is to control a system, often called the plant, so its output follows a desired control signal, called the reference, which may be a fixed or changing value. To do this a controller is designed, which monitors the output and compares it with the reference. The difference between actual and desired output, called the error signal, is applied as feedback to the input of the system, to bring the actual output closer to the reference. Some topics studied in control theory are stability (whether the output will converge to the reference value or oscillate about it), controllability and observability.[5]

3.4.1 Classical Control Theory

To overcome the limitations of the open-loop controller, control theory introduces feedback. Closed-loop controller uses feedback to control states or outputs of a dynamical system. Its name comes from the information path in the system: process inputs (e.g., voltage applied to an electric motor) have an effect on the process outputs (e.g., speed or torque of the motor), which is measured with sensors and processed by the controller; the result (the control signal) is "fed back" as input to the process, closing the loop.

Closed-loop controllers have the following advantages over open-loop controllers:

1. Disturbance rejection (such as hills in the cruise control example above).
2. Guaranteed performance even with model uncertainties, when the model structure does not match perfectly the real process and the model parameters are not exact.
3. Unstable processes can be stabilized.
4. Reduced sensitivity to parameter variations.
5. Improved reference tracking performance.

In some systems, closed-loop and open-loop control are used simultaneously. In such systems, the open-loop control is termed feed forward and serves to further improve

reference tracking performance. Common closed-loop controller architecture is the PID controller.[6]

3.4.2 Modern Control Theory

In contrast to the frequency domain analysis of the classical control theory, modern control theory utilizes the time-domain state space representation, a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations. To abstract from the number of inputs, outputs and states, the variables are expressed as vectors and the differential and algebraic equations are written in matrix form (the latter only being possible when the dynamical system is linear).[7]

The state space representation (also known as the "time-domain approach") provides a convenient and compact way to model and analyse systems with multiple inputs and outputs. With inputs and outputs, we would otherwise have to write down Laplace transforms to encode all the information about a system.

Unlike the frequency domain approach, the use of the state-space representation is not limited to systems with linear components and zero initial conditions. "State space" refers to the space whose axes are the state variables. The state of the system can be represented as a vector within that space.

3.4.3 Optimal Control Theory

Optimal control deals with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. A control problem includes a functional that is a function of state and control variables. An optimal control is a set of differential equations describing the paths of the control variables that minimize the cost functional. The optimal control can be derived using Pontryagin's maximum principle (a necessary condition also known as Pontryagin's minimum principle or simply Pontryagin's Principle), or by solving the Hamilton–Jacobi–Bellman equation (a sufficient condition).

3.5 Control Design Objectives

1. Regulation: keep controlled variable near a constant target value (e.g. process control: pressure, concentration etc.).

2. Tracking: keep controlled variable near a time-varying target value (e.g. antenna positioning, robotic manipulator point-to point manoeuvre, motor speed/position control).
3. Stability, roughly means bounded output for bounded input,
4. Accuracy means minimum steady state error.
5. Satisfactory transient behaviour means minimum or zero overshoot, fast response (less rise and settling times).
6. Robustness means less sensitivity to real operating conditions abrupt changes.

3.6 Types of Controllers

Most control systems in the past were implemented using mechanical systems or solid state electronics. Pneumatics was often utilized to transmit information and control using pressure. However, most modern control systems in industrial settings now rely on computers for the controller. Obviously it is much easier to implement complex control algorithms on a computer than using a mechanical system.

3.6.1 Proportional Controllers

We cannot use types of controllers at anywhere, with each type controller; there are certain conditions that must be fulfilled. With proportional controllers there are two conditions and these are written below:

- 1- Deviation should not be large; it means there should be less deviation between the input and output.
- 2- Deviation should not be sudden.

Now we are in a condition to discuss proportional controllers, as the name suggests in a proportional controller the output (also called the actuating signal) is directly proportional to the error signal. Now let us analyse proportional controller mathematically. As we know in proportional controller output is directly proportional to error signal, writing this mathematically we have,

$$A(t) \propto e(t) \dots \dots \dots (3.4)$$

Removing the sign of proportionality we have,

$$A(t) = Kp \times e(t) \dots \dots \dots (3.5)$$

Where:

Kp is proportional constant also known as controller gain. It is recommended that Kp should be kept greater than unity. If the value of Kp is greater than unity, then it will amplify the error signal and thus the amplified error signal can be detected easily. Proportional controller helps in reducing the steady state error, thus makes the system more stable. Slow response of the over damped system can be made faster with the help of these controllers. Now there are some serious disadvantages of these controllers and these are written as follows:

1. Due to presence of these controllers there are some offsets in the system.
2. Proportional controllers also increase the maximum overshoot of the system.

3.6.2 Integral Controllers

As the name suggests in integral controllers the output (also called the actuating signal) is directly proportional to the integral of the error signal. Now let us analyze integral controller mathematically. As we know in an integral controller output is directly proportional to the integration of the error signal, writing this mathematically we have,

$$A(t) \propto \int_0^t e(t) dt \dots \dots \dots (3.6)$$

Removing the sign of proportionality we have,

$$A(t) = Ki \times \int_0^t e(t) dt \dots \dots \dots (3.7)$$

Where:

Ki is integral constant also known as controller gain. Integral controller is also known as reset controller. Due to their unique ability they can return the controlled variable back to the exact set point following a disturbance that's why these are known as reset controllers. Integral Controller has advantages that it tends to make the system unstable because it responds slowly towards the produced error.

3.6.3 Derivative Controllers

We never use derivative controllers alone. It should be used in combinations with other modes of controllers because of its few disadvantages which are written below:

1. It never improves the steady state error.
2. It produces saturation effects and also amplifies the noise signals produced in the system.

Now, as the name suggests in a derivative controller the output (also called the actuating signal) is directly proportional to the derivative of the error signal. Now let us analyze derivative controller mathematically. As we know in a derivative controller output is directly proportional to the derivative of the error signal, writing this mathematically we have,

$$A(t) \propto \frac{de(t)}{dt} \dots\dots\dots (3.8)$$

Removing the sign of proportionality we have,

$$A(t) = Kd \times \frac{de(t)}{dt} \dots\dots\dots (3.9)$$

Where:

Kd is proportional constant also known as controller gain. Derivative controller is also known as rate controller. The major advantage of derivative controller is that it improves the transient response of the system.[8]

3.6.4 PID Controller

The PID controller calculation (algorithm) involves three separate parameters; the Proportional, the Integral and Derivative values. The Proportional value determines the reaction to the current error, the Integral determines the reaction based on the sum of recent errors and the Derivative determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element.

Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are particularly common, since derivative action is very

sensitive to measurement noise, and the absence of an integral value may prevent the system from reaching its target value due to the control action.

3.6.5 Proportional and Integral Controller

As the name suggests it is a combination of proportional and an integral controller the output (also called the actuating signal) is equal to the summation of proportional and integral of the error signal. Now let us analyse proportional and integral controller mathematically. As we know in a proportional and integral controller output is directly proportional to the summation of proportional of error and integration of the error signal, writing this mathematically we have,

$$A(t) \propto \int_0^t e(t) dt + A(t) \propto e(t) \dots \dots \dots (3.10)$$

Removing the sign of proportionality we have,

$$A(t) = Ki \int_0^t e(t) dt + Kp e(t) \dots \dots \dots (3.11)$$

Where:

Ki and Kp are proportional constant and integral constant respectively.

Advantages and disadvantages are the combinations of the advantages and disadvantages of proportional and integral controllers.

3.6.6 Proportional and Derivative Controller

As the name suggests it is a combination of proportional and a derivative controller the output (also called the actuating signal) is equals to the summation of proportional and derivative of the error signal. Now let us analyse proportional and derivative controller mathematically. As we know in a proportional and derivative controller output is directly proportional to summation of proportional of error and differentiation of the error signal, writing this mathematically we have,

$$A(t) \propto \frac{de(t)}{dt} + A(t) \propto e(t) \dots \dots \dots (3.12)$$

Removing the sign of proportionality we have,

$$A(t) = Kd \frac{de(t)}{dt} + Kpe(t) \dots \dots \dots (3.13)$$

Where:

K_d and K_p are proportional constant and derivative constant respectively.

Advantages and disadvantages are the combinations of advantages and disadvantages of proportional and derivative controllers. By "tuning" the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability.

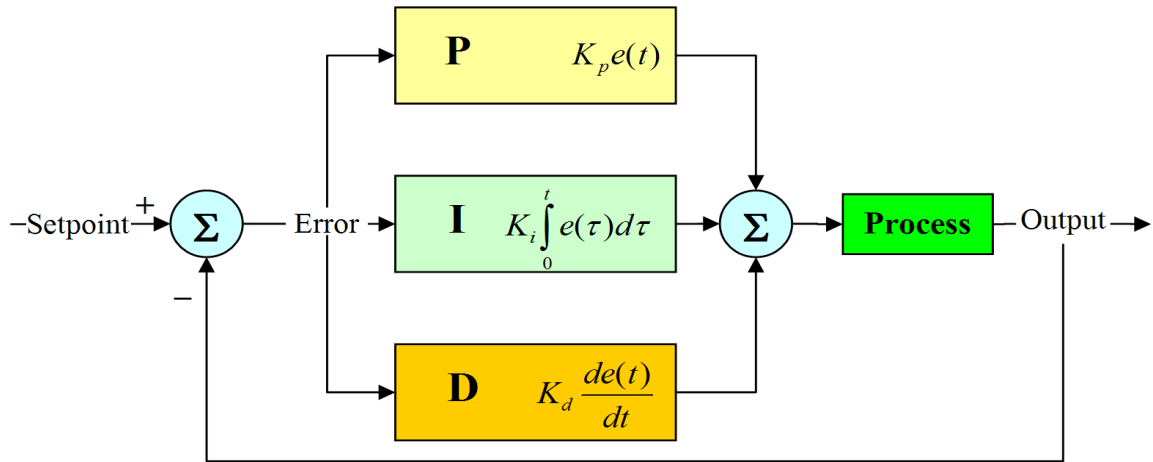


Figure 6: PID Controller Block Diagram

Table 1: Effects of each of controller K_p , K_d , and K_i on a closed-loop system

CL RESPONSE	RISE TIME	OVERSHOOT	SETTLING TIME
K_p	Decrease	Increase	Small Change
K_i	Decrease	Increase	Increase
K_d	Small Change	Decrease	Decrease

NOTE

The transient response of a practical control system often exhibits damped oscillations before reaching steady state. In specifying the transient-response characteristics of a control system to a unit-step input, it is common to specify the following:

Delay time (t_d): The delay time is the time required for the response to reach half the final value the very first time.

Rise time (t_r): The rise time is the time required for the response to rise from (10% to 90%), (5% to 95%) or (0% to 100%) of its final value. For under damped second order systems, the (0% to 100%) rise time is normally used. For over damped systems, the (10% to 90%) rise time is commonly used.

Peak time (t_p): The peak time is the time required for the response to reach the first peak of the overshoot.

Maximum (per cent) overshoot: The maximum overshoot is the maximum peak value of the response curve measured from unity.

Settling time (t_s): The settling time is the time required for the response curve to reach and stay within a range about the final value of size specified by absolute percentage of the final value (usually 2% or 5%).

These specifications are shown graphically in figure [7].

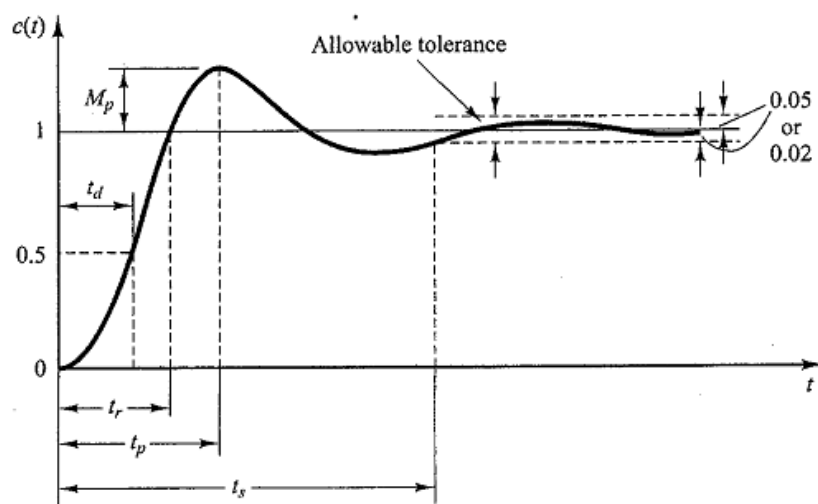


Figure 7: Transient and Steady-State Response Analyses source [9]

Implementing control theories and tools in aircraft engines is one of the most interesting fields of engineering. It is not always valuable to use same controller, it is highly dependent on the states of the system and dynamics.

Aircraft engine automatisation gone through many stages and have different concepts, but they all sub into maintaining stability and reducing cost. Autothrottle is a main topic to look at while reaching FADEC (Full Authority Digital Engine Control).[9]

3.7 Full Authority Digital Engine Control (FADEC)

It takes complete control of engine systems in response to command inputs from the aircraft. It also provides information to the aircraft for flight deck indicators, engine condition monitoring, and maintenance reporting and troubleshooting.[10]

3.7.1 FADEC Components

1. Engine Control Unit (ECU): It performs engine control calculations and monitors the engine's condition.
2. Hydro-mechanical Unit (HMU): It converts electrical signals from the ECU into hydraulic pressure to drive the engine's valves and actuators.
3. Peripheral components: such as valves, actuators and sensors used for control and monitoring.

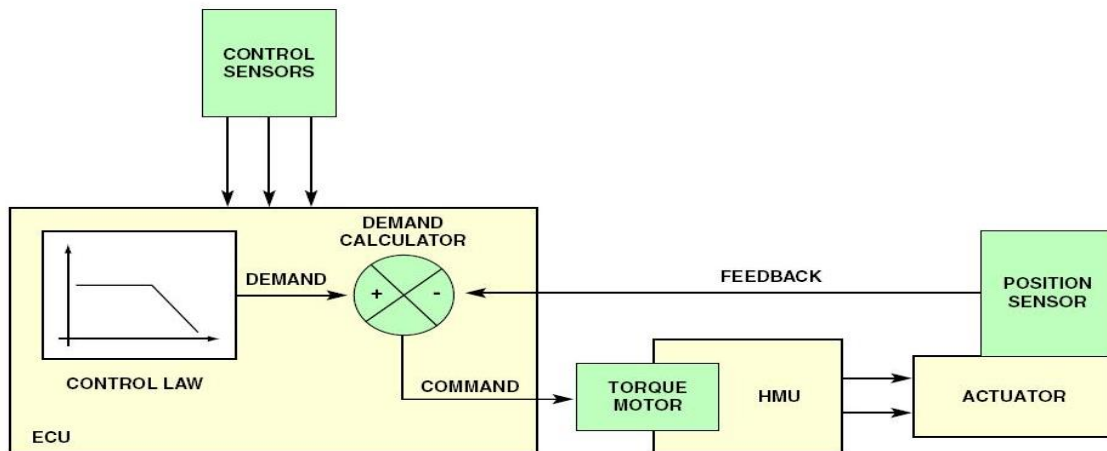


Figure 8: FADEC Control Philosophy

Chapter 4: Autothrottle system

4.1 Background and Operation

The first-ever auto throttle was a primitive system in the World War II-era German Me-262 jet fighter. The first viable commercial system was installed in a DC-3 in 1956 (two years before the speedostat cruise control was introduced in the Chrysler Imperial). That first system was called Auto Power. The inventor was Leonard Greene, who founded Safe Flight Instrument Corp. and was a pioneer in stall warning and angle-of-attack equipment.

Greene's speed control device connected servos to the throttles that automatically adjusted to maintain a given angle of attack not an air speed. When the pilots turned the system on to fly an approach, it commanded the power levers to maintain a speed corresponding with 1.3 times of stall speed in the landing configuration (V_{S0}). It worked, but the concept didn't really catch on until Safe Flight linked it to airspeed and not just angle of attack. The modern auto throttle was born.

An unusual element of Safe Flight's auto throttles is a patented safety feature called the "voter." It allows the auto throttle system to compare the speed selected by the pilots with $1.3 V_{S0}$ and automatically chooses the higher of the two. This prevents an airplane from stalling with the autothrottle engaged if the pilot dials in a speed below reference speed V_R , even at steep bank angles with high load factors or at heavy weights. Safe flight's entire auto throttles to this day, including the systems the company designed for the Gulfstream GII and GIII and in the Challenger 604 and 605 business jets (as well as military aircraft including the F-117 stealth fighter) employ the voter concept.

It wasn't long before competitors got into the auto throttle game as Sperry (now part of Honeywell) and Collins began developing auto throttle systems for a growing number of airliners and bizjets. Today auto throttle is standard on most large-cabin bizjets and airliners, and it's coming to more midsize jets as well. On these auto throttle equipped airplanes, the system can automatically fly the glide slope and maintain speed to within a hair's breadth of the target, leading to predictably safe and stable approaches (and landings).[11]

Table 2: Basic Auto throttle Functions over the Flight Profile.

No	Flight Phase	Flight Director Mode	Auto throttle Function	Autopilot Function
1	Take-off	Take-off	Maximum rated thrust	N/A
2	Climb-out	Flight Level Change	Take-off to Climb thrust transition	Airspeed Control
3	Small-step Climb	Flight Level Change	Reduced climb thrust for smooth transition	Airspeed Control
4	Large-step	Flight Level Change	Full climb thrust	Airspeed Control
5	Top-of-Climb	Altitude Capture	Transition to airspeed control	Altitude Capture
6	Cruise	Altitude Hold	Airspeed control	Altitude Hold
7	Top-of-Descent	Flight Level Change	Transition to minimum thrust	Airspeed Control
8	Descent	Flight Level Change	Maintain minimum thrust	Airspeed Control
9	Approach	Glideslope Track	Airspeed control	Glideslope Track
10	Landing	N/A	Disengage	Disengage
11	Go-Around	Go-Around	Maximum rated thrust	Disengage

4.1.1 Operation

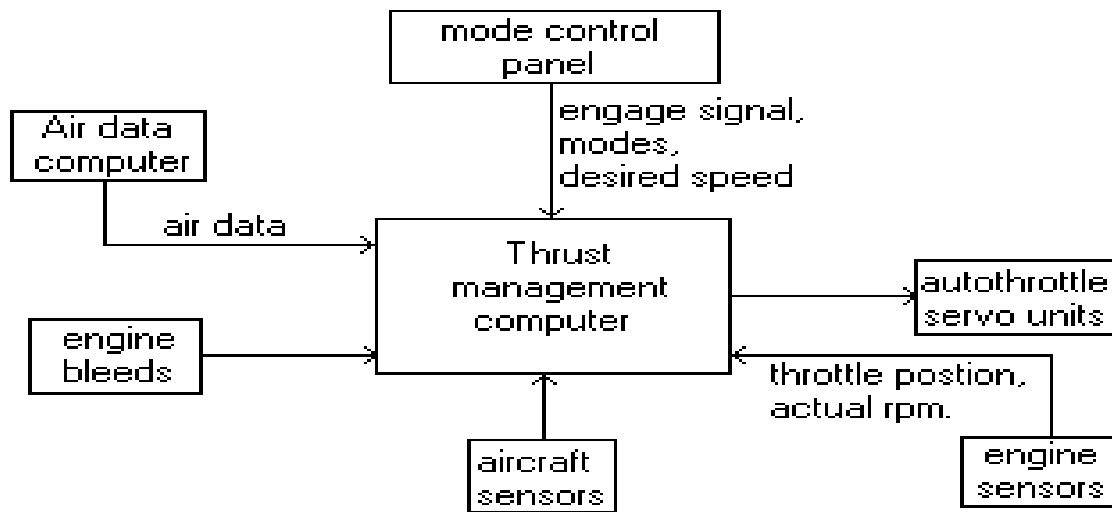


Figure 9: Autothrottle Unit

The thrust management computer (TMC) receives data from various systems, then computes the information that will affect the operation of the auto throttle system, then sends the information to the servo units in the auto throttle system to drive the throttles to a selected position, the TMC receives information from the engine & aircraft sensors to null any movement of the thrust levers once the desired speed has been achieved.

There are two modes of operation in the auto throttle system:

1. **Speed mode:** which controls the speed of the aircraft, this mode is used during climb, cruise & landing stages only.
2. **EPR mode:** controls the engine pressure ratio (EPR) during the take-off stage of the aircraft.

For purposes of air conditioning and pneumatic systems, a reduction in thrust occurs, these losses are called engine bleeds, and the TMC uses this information to calculate the losses due to the bleed extraction and to compensate these losses.[12]

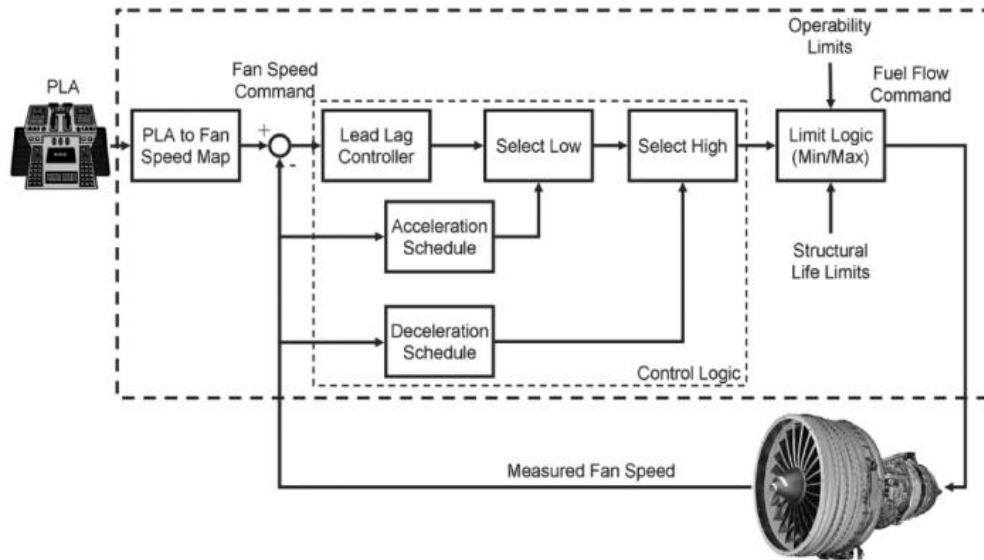


Figure 10: Block Diagram of Typical Modern Engine Control Logic (image courtesy of NASA). Source [4]

An autothrottle system for FADEC equipped aircraft includes a remote friction element which is separated from a pilot's console. The system also includes an autothrottle control and a manual throttle control which are mechanically coupled through the friction element. The friction element provides the "feel" of a cable operated throttle system and allows a pilot to manually override the auto throttle without a significant change in the torque required to advance or retard the throttle. The system also includes a servo motor, gear drive and shaft with the friction element disposed on the shaft. A mechanical coupling connects the shaft and the manual control so that any changes caused by the auto throttle cause a corresponding change in a pilot's manual throttle control.

An autothrottle system for an aircraft includes a throttle lever actuator which is easily retrofitted to an existing throttle quadrant and employs a D.C. stepping motor to slew the throttle levers and eliminate the need for a feedback loop.

Current commercial aircraft include the capability to be on either manually or using automatic control systems. For example, in many aircraft, it is typical to have an auto throttle, an autopilot, and a Flight Management Computer (FMC). Each of these systems is interrelated to the others, with a hierarchy of control levels existing between the systems, management computers are arranged to control both, the autopilot and the

auto throttle, autopilots are arranged to control the auto throttle, etc. By adding a Mode Control Panel (MCP), a Wide range of flight modes become available for use by the pilot. When landing an aircraft (either manually or using an automatic mode), it is typical to use the auto throttle to reduce the engine thrust to idle. When the aircraft reaches a certain altitude. For example during an automatic landing, upon reaching 24 feet, the auto throttle will move the engine control lever to idle. The rate at which the lever is moved depends on the existing lever position, e.g., a lever position that is already close to idle will move slower than a lever position that is farther from idle. Typical throttle lever rate movements are between about 2.2 degrees per second to about 1.7 degrees per second. A negative sign refers to a resulting reduction in engine throttle setting. The vertical rate at which the aircraft actually lands on the runway (referred to as the vertical speed or sink rate at touchdown) is often influenced by current Wind and Weather conditions, and is quite dependent upon the reduction of throttle to idle. During the aircraft landing manoeuvre, Wind changes that reduce the airplane airspeed (referred to as an under speed condition) may result in a reduction of airplane elevator effectiveness and in a high sink rate at touchdown. This maybe felt as a hard bump at touchdown, which can cause discomfort to some passengers and can cause wear to the landing gear. Under speed conditions are also associated with short landing distances.

Autothrottle is used to maintain a specific airspeed or thrust automatically, without the pilot having to constantly adjust the throttles by hand. This allows the pilot to, say, climbs or descends in the airplane without having to touch the throttles the auto throttle adjusts the engines as required to maintain the desired thrust or airspeed. It can be used in many other phases of flight, too. The main idea is just to lighten the workload on the pilot(s).[13]

4.2 Air Traffic Control

It is the responsibility of ATC to provide clearances to the crew based on known traffic and physical airport conditions. States that ATC may clear an aircraft to a different altitude or route due to traffic conditions.

While complying with a speed adjustment from ATC, the crew must maintain a speed within plus or minus 0.02 Mach number of the speed specified, unless this is outside the

safe operating speed of the aircraft. Changes to this policy could improve fuel efficiency. Approximately 6-12 percent of fuel burned could be saved by more efficient flight plans and decreasing holding patterns.

In the impact on fuel consumption when a faster airplane follows a slower airplane is analysed for a range of 100 nautical miles and three different altitudes. This research showed that an aircraft's performance can be reduced by up to 11 percent when forced to follow a slower airplane.

There are two types of throttle control proposed in literature. First is a total energy control system (TECS) that combines pitch and throttle control into one multi-input multi-output (MIMO) control law. The second is a single-input single-output (SISO) architecture that has two separate control laws for pitch and throttle. The thrust output of these control laws is a throttle rate command. This gives the pilot visibility as to what the auto throttle is commanding. This visual feedback was not provided on the A320, a survey of the pilots of this aircraft was conducted, while not having back driving the throttles had some advantages, it was concluded that providing movement of the throttles was preferred.[11]

4.3 Autothrottle System Design

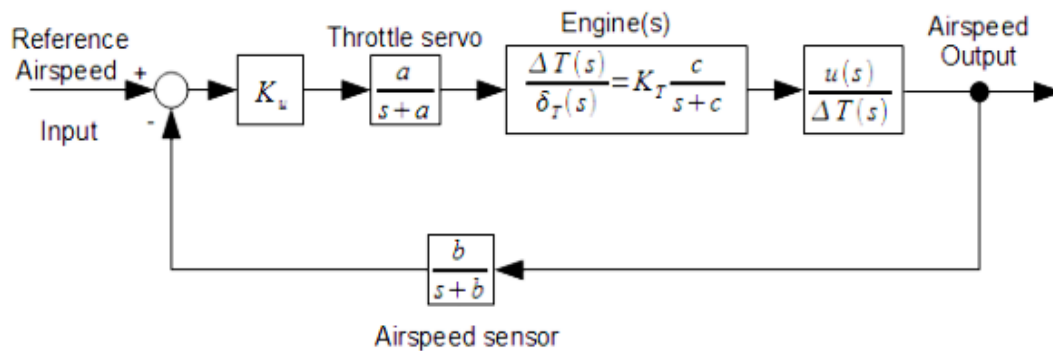


Figure 11: Proposed Block Diagram by Rebecca

According to **Rebecca Marie Johnson's** research, there are two basic closed-loop functions in the SISO autothrottle: thrust control and airspeed control. During the cruise phase of flight, the autothrottle is in a speed-hold mode. In this mode the autothrottle

control law commands the throttles to hold the selected airspeed. Figure [11] shows a simple autothrottle airspeed loop. In figure [11] K_u represents the autothrottle control law. The throttle servo block is a model of the mechanical servo inside the TQA. The engines are modelled with a gain, K_T , of throttle position to thrust 15 (lbs/degree) and a lag. The last block of the plant is the transfer function of thrust to airspeed, which is a simplified model of the airplane dynamics. The feedback of the airspeed includes another lag to model the filtering present inside the air data sensor a major design compromise is represented by balancing control accuracy and dynamic response with throttle activity. A typical flight crew makes steady and infrequent movements of the throttles, and the autothrottle is expected to mimic this behaviour. Passenger comfort is also taken into consideration, since they are able to hear adjustments to the engines and feel changes to aircraft accelerations. Since high-altitude cruise can be the longest phase of flight, passenger comfort and minimal throttle activity was considered to be the top priority. While controlling airspeed, a wind gust can create a speed error equal in magnitude to that of the gust. However, given the bandwidth of this loop, adjusting throttles to compensate for winds, especially turbulence, could cause continuous cycling of the throttles. In this situation the crew would set the throttle to a nominal position.

4.4 Summary

Results are not accurate due to losses in fuel every time fuel valve adjusted with each throttle position is change. This may not be accurately modelled in this simulation, because the lack of data. As such, they are still not quite matched to the generic simulation.

Next in chapter five a simple design will be simulated in MATLAB, using the throttle as servo and engine dynamic as a second order transfer function for a general jet engine.

Chapter 5: Simulation of Autothrottle using MATLAB

As seen through literature review *Rebecca Marie Johnson's* team concluded that values for fuel flow rate was not accurate because the lack of data. Here in this chapter we will try to solve the problem of weak response of the fuel valve that may affect the fuel consumption and fuel flow rate by designing a controller and simulate it.

5.1 Relation between Thrust, Aircraft Speed and Engine RPM

To increase the thrust of a turbojet engine in flight, it is necessary to increase fuel mass flow rate. This throttling then increases the exit velocity of air and gives increased thrust. Specific thrust in turbofan engine for example depends only on the velocity difference produced by the engine; velocity difference in gas is a pressure. So, how much thrust the engine will generate depends on how big of a dynamic pressure difference it can create in the air between its front and back. We need to see if added RPM creates added thrust, yes it does. Providing the engine with more fuel will create faster escaping hot gases from the burner. Those will create a bigger dynamic pressure difference between the burner and the nozzles then the turbine run faster. Power from the turbine is moved to the compressor which will also turn faster thus pushing out more air.

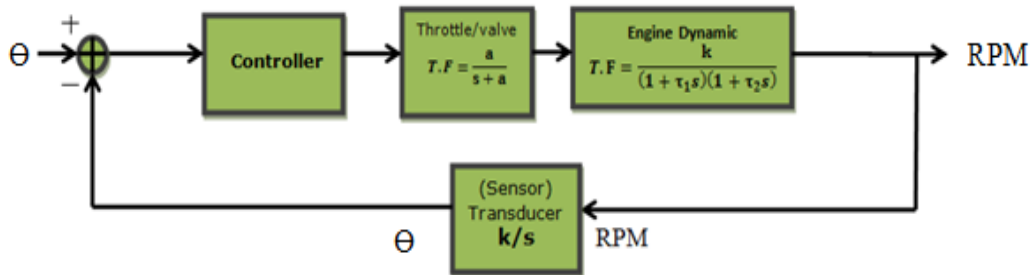


Figure 12: Simplified Proposed Block Diagram for Auto-throttle

There are two basic closed-loop functions in the SISO auto throttle: thrust control and airspeed control. In this mode the auto throttle control law commands the throttles to hold the selected airspeed.

1. Engine Dynamic

$$T.F = \frac{k}{(1+\tau_1 s)(1+\tau_2 s)} \dots\dots\dots (5.1)$$

Table 3: Variables Table

No	τ_1	τ_2
1	0.1	0.01
2	2.3	0.07
3	3	0.1

Where:

K is the gain. τ_1, τ_2 are the engine time constants.

τ_1 Represent of the engine coefficients.

τ_2 Represent of the engine valve coefficients

We check the system stability by obtaining root locus using MATLAB.

Those values give us the wide range of stability (-10 , -100) as shown in figure[13] below :

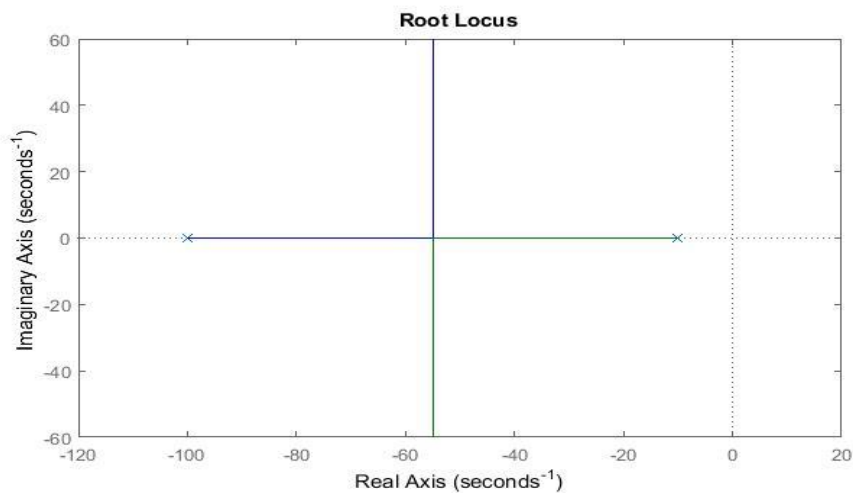


Figure 13: Root Locus

2. Throttle

The throttle servo block is a model of control valve. The last block of the plant is the transfer function. We use a simple control valve as a throttle. The function of a control valve is to modulate the flow of a process fluid in accordance with some external signal, usually generated by the controller. The important performance characteristics, from the standpoint of control, are determined by the relationships between flow, pressure, and valve travel. Other practical application considerations are valve body pressure ratings, shutoff requirements, material selection, valve style, valve size, recovery characteristics, and valve characterization.

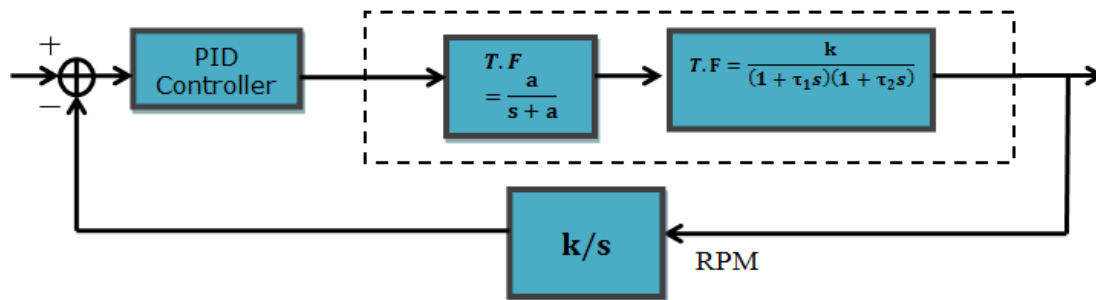


Figure 14: Sub system, throttle command

3. Controller

It is the main controller in this circuit, which is P, I, D or PID controllers. Also the PID controller is a good hardware and its work can be simulated by any advanced software.

4. Transducer

The feedback of the airspeed includes another lag to model the filtering present inside the air data sensor (transducer sensor) modelled with gain (k/s).

Secondly, by using some means of logic programs like: C, C++, or MATLAB, hence, the controller can be simulated. Here in the research MATLAB had been chosen.

MATLAB (MATRIX LABROTORY) have many features in using the mathematical and control functions.

The functions used in the design algorithms are defined as follow:

tf: create transfer function; which classified as a model function.

Feedback: calculate the feedback connection of models; which classified as a model interconnections function.

Step: calculate step response; which classified as a time response function.

PID tool: enables to identify the controlled process from its step response and run filtration. PIDTOOL also enables to tune various types of PID controller such as P, PI, PID or PD controllers to get desirable response.

5.2 Results

M-file have been used to plot the response, then for the controller, PID tool used. Responses with discussions are in figures below:

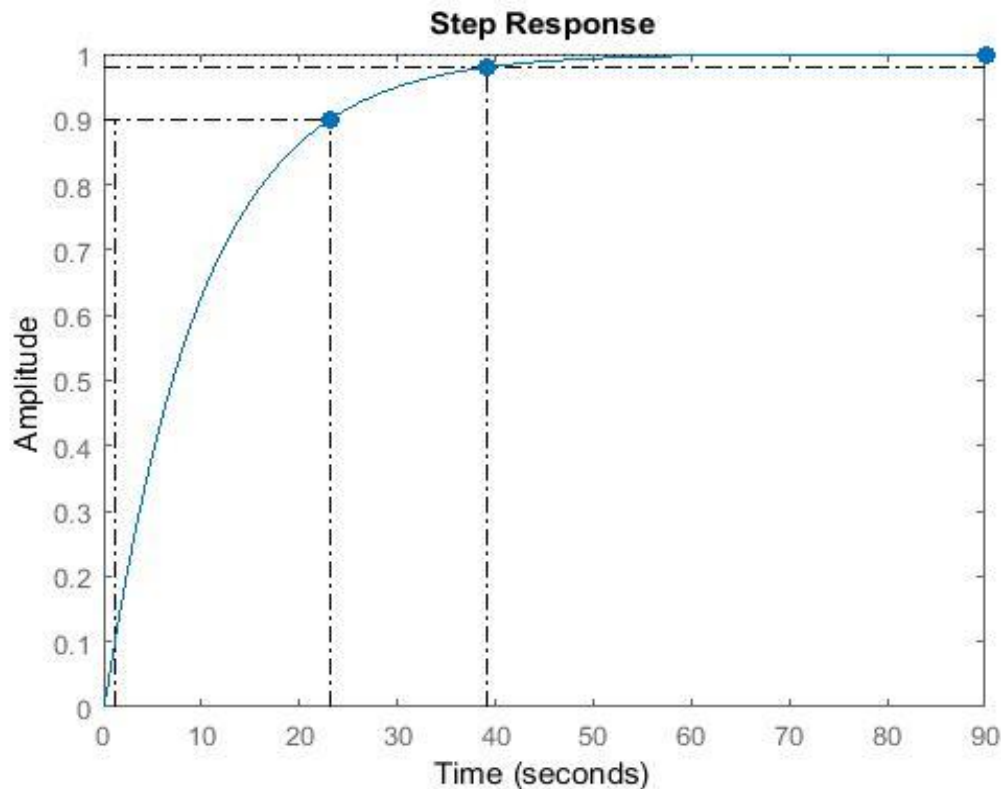


Figure 15: Open Loop Step Response

Steady state (final value) = 1

Rise time (sec) = 22

Settling time (sec) = 39.2

Figure [15] above shows the response for the subsystem in figure [14], clearly the system will stay too long in the transient response with almost no transient error. It is a common case for open loop systems and can be enhanced by closing the loop using a transducer with integration.

5.2.2 PID Tool

Conditions:

Response time (second) = 0.27

Transient behaviour (second) = 0.6

1) P controller

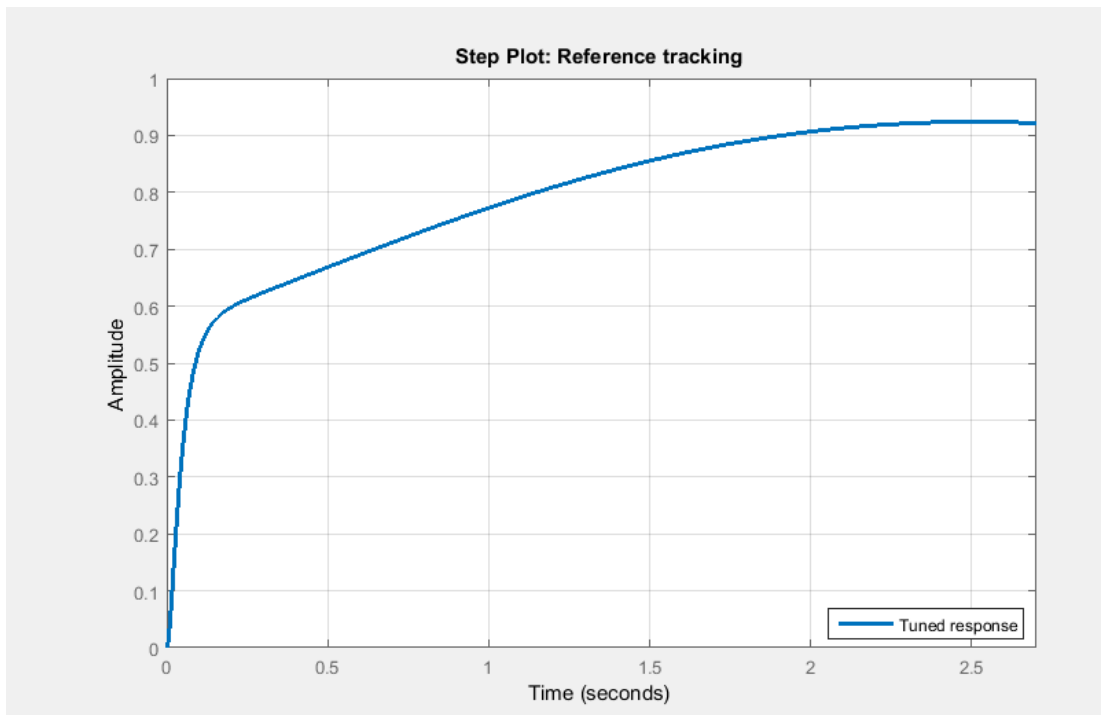


Figure 16: System with P Controller Time Response

Rise time (sec) = 1.75

Settling time (sec) = 48.5

Over shoot=INF.

In figure [16] above, when a proportional controller added both settling time and overshoot increased while rise time decreased.

2) I controller

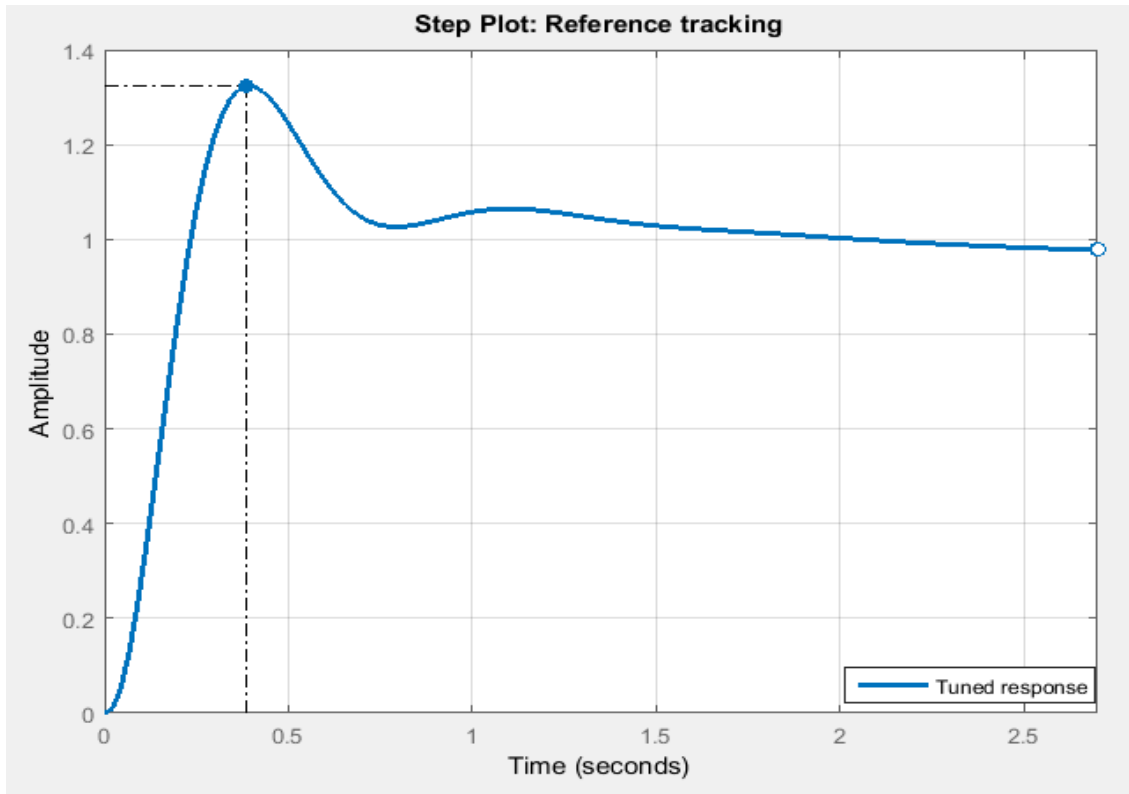


Figure 17: System with I controller time response

Rise time (sec) = 0.153

Settling time (sec) = 3.61

Over shoot (%) = 33.9

For I controller case in figure [17] above rise time is decreased because the overshoot is increased.

The combination of the three controllers P, I and D is then a good choice in order to maintain the system stability and fasten the response.

3) PID controller

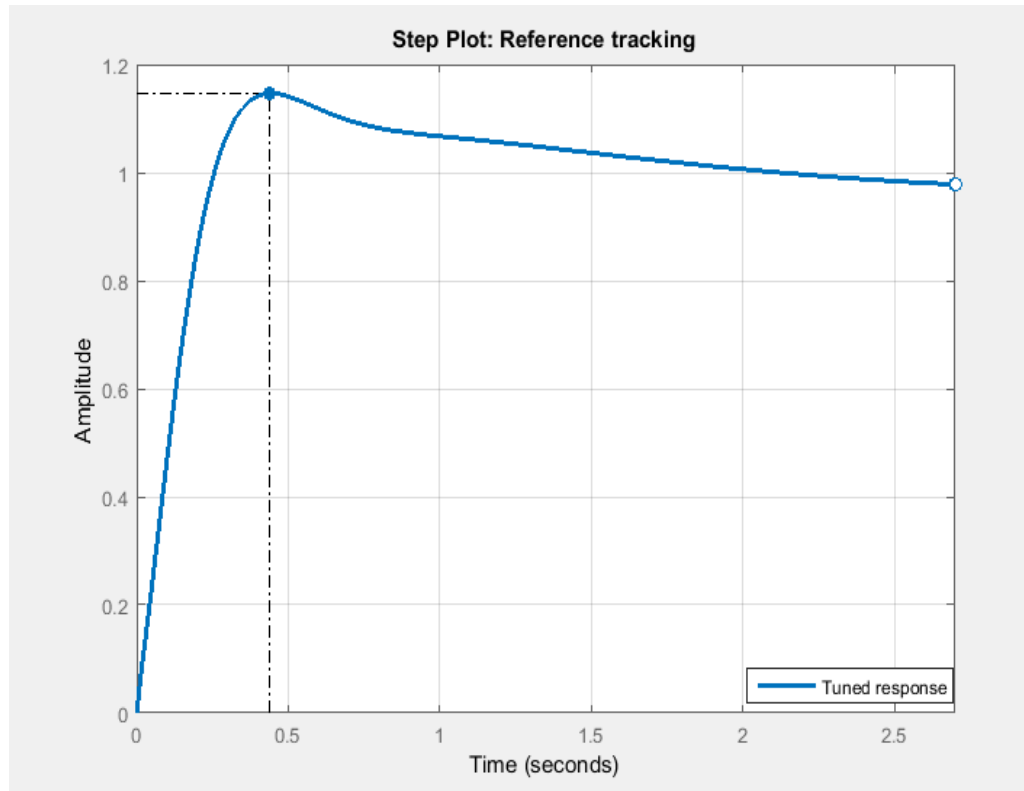


Figure 18: System with PID Controller Time Response

Rise time (sec) = 0.19

Settling time (sec) = 3.89

Over shoot (%) = 15.9

From figure [18] both settling and rising time are decreasing, but there is a still an overshoot by 15.9 %. Eliminating the D controller while saving the same tuning results in increasing the overshoot to 17.9 %, but the system became more reliable and faster as can see in figure [19] below. Overshoot problems can be solved by adding a limiter in a real controller or controlling environment when using SIMULINK, here with PID tool tuning the transient behaviour and robustness made it easy to find a response that can maintain the stability and the values for the controllers gains can then be taken from the characteristics.

4) PI controller

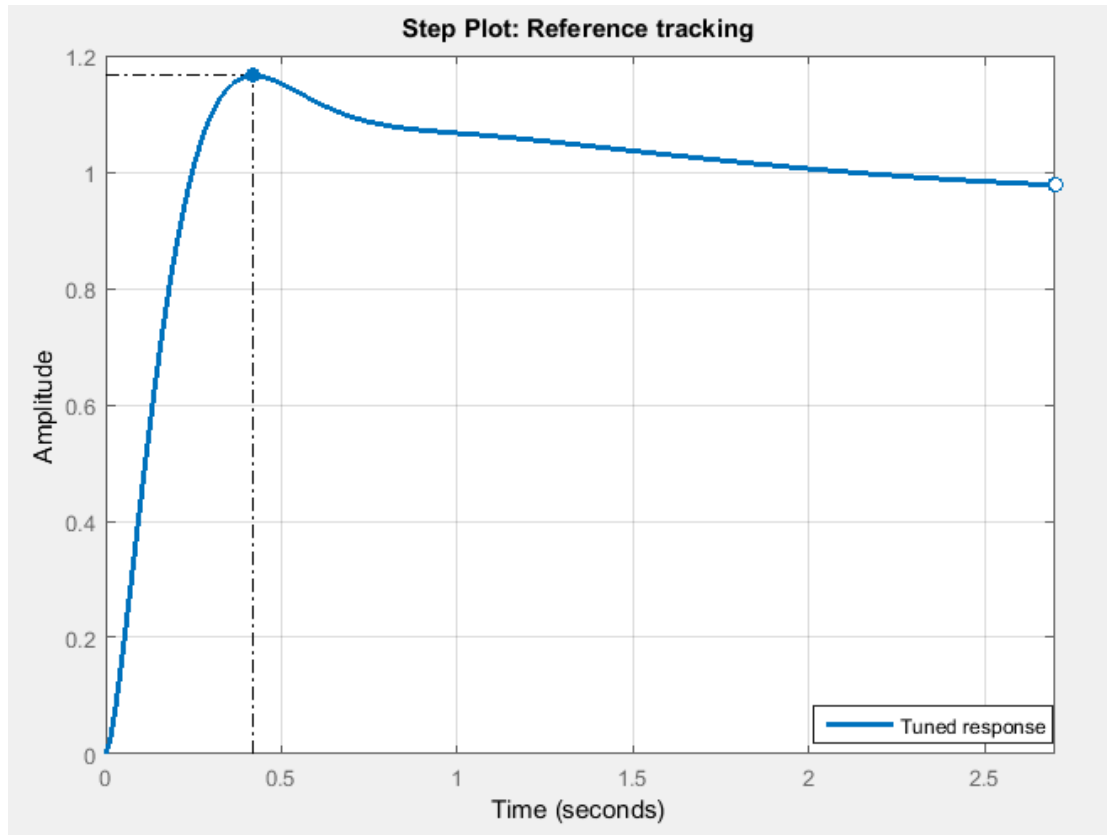


Figure 19: System with PI Controller Time Response

Rise time (sec) = 0.174

Settling time (sec) = 3.91

Over shoot (%) = 17.8

As a final result, taking into account the output responses in figures above it can be clearly seen that after more practices in P, I, D and PID, we found PI controller response is more precise especially when tuned to $K_p=40.04$ and $K_i= 324.66$. The response is as shown in figure [20] below.

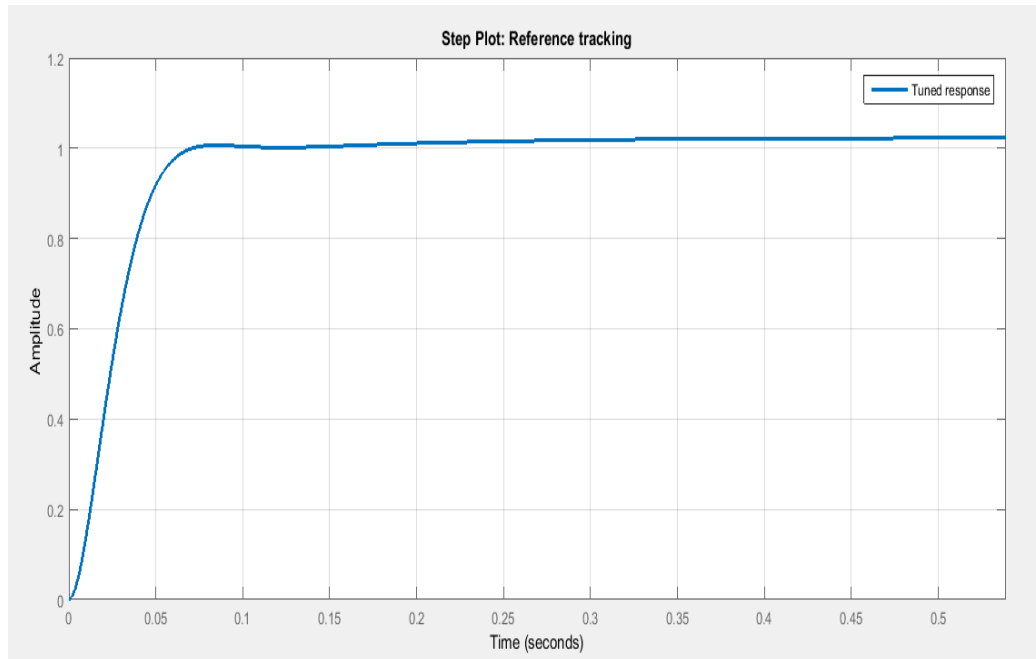


Figure 20: Best PI Controller Time Response

The response we found is:

- Fast rise time (sec) = 0.039
- Minimum overshoot (%) = 0.0885

Chapter 6: Conclusion and Recommendation

By the end of this project a lot of skills have been earned and important knowledge acquired. The overlapping between the electrical, electronics and programming makes it deserves to spend the time on it to apply and manage the engineering work.

6.1 Conclusion

Generally the project was capable to meet up the objectives of it. The aim of the project was to study the effect of implementing autothrottle on reducing pilot workload and fuel consumption, what claimed to increase the range of the aircraft and reduce flight cost, by design and control a simple auto-throttle. The design proposed was able to do this job and the response from the system supported the theory.

Most of the objectives of this project had been met and the overall performance of the system was good but still having problems with the equations that relating airspeed and range to rate of fuel consumption.

Generally, using PI controller gave a faster response to open and close the valve of the fuel injection, but at the expense of requiring more electronics with which to operate the throttle. There is a lot that can be done for the engine itself, controlling circuit and the software in order to enhance the performance.

6.2 Future work

Here are some suggestions for further work:

1. The speed equation:
2. Use fuel flow rate equation: $\dot{m}_f = \dot{m}_T \cdot F$ to drive a control law while considering Θ as input and engine RPM as output.
3. Hardware design microcontroller using one of the available PIKT, Θ as input, engine coefficients as interrupts.
4. Another interrupt can be added or can use the switches in the PIKT to do this. To simulate different flight stages.
5. Taking the study to higher levels, by applying the theory to turbofan engine as the most fuel efficient engine, adaptive controller will be needed in order to do so.

Reference

- [1] I. Husain and S. A. Hossain, "Modeling, simulation, and control of switched reluctance motor drives," *Industrial Electronics, IEEE Transactions on*, vol. 52, pp. 1625-1634, 2005.
- [2] "د.إ.ع.أ.م. خطاب, "بناء وتصميم المحركات التوربينية للطائرات"
- [3] R. Stone, *Introduction to internal combustion engines*: Palgrave Macmillan, 2012.
- [4] S. G. a. N. G. R. Center, "Aircraft Turbine Engine Control Research ".
- [5] G. Pahl and W. Beitz, *Engineering design: a systematic approach*: Springer Science & Business Media, 2013.
- [6] K. J. Åström and B. Wittenmark, *Adaptive control*: Courier Corporation, 2013.
- [7] E. D. Sontag, *Mathematical control theory: deterministic finite dimensional systems* vol. 6: Springer Science & Business Media, 2013.
- [8] N. S. Nise, *CONTROL SYSTEMS ENGINEERING, (With CD)*: John Wiley & Sons, 2007.
- [9] K. Ogata and U. o. Minnesota, *Modern Control Engineering 4th Ed*
- [10] E. L. Wiener and R. E. Curry, "Flight-deck automation: Promises and problems," *Ergonomics*, vol. 23, pp. 995-1011, 1980.
- [11] R. M. Johnson and I. S. University, "Using an autothrottle to compare techniques for saving fuel".
- [12] A. Ahmoudy, "aircraft autothrottle system S.P."
- [13] D. S. Garg and C. a. D. B.-G. R. C. Chief, "Fundamentals of Aircraft Turbine Engine Control."

Appendix

MATLAB algorithm

```
t1=0.1;
t2=0.01;
a=0.1;
num=[1];
den=[t1*t2 t1+t2 1];
Gp=tf(num,den);
Gt=tf([a],[1 a]);
sys=series(Gp,Gt);
h=tf([1],[1 0]);
sys1=feedback(sys,h);
step(sys1);
Kp=1;Ki=1;Kd=1;
C=pid(Kp,Ki,Kd);
sys2=feedback(sys*C,h);
t=0:.1:2;
step(sys2,t);
pidtool(sys2);
grid on
```