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Closed Loop Fuel Control of Aero Engine

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Abstract—
The fuel system is the most important fluid system in the aircraft. It has a more profound effect on aircraft performance than any other airframe system. This paper provides an overview of design and control of the aircraft fuel engine system. This is an indigenous project where we have designed the fuel flow control system. This helps to understand the top requirements required by the pilot about the speed, pressure which in turn helps to control the fuel flow of an aero engine.
Aero engine is a typical nonlinear system; the main fuel control system is the core of the aircraft engine system. Hence we propose this project where the fuel flow control system is designed in a simple and effective way.
The fuel flow control is obtained by monitoring the steps of a stepper motor and by taking many considerations such as pressure and speed. The speed is measured in terms of rotations per minute (rpm). Basically high rpm means more flow and hence the control of the rpm should be made compatible with the fuel intake. The decision is taken based on the feedback obtained from the fuel flow control system. Digital electronic control unit compares the actual engine speed with demanded speed and then it gives back to controller as an error signal. The fuel flow depends on this error signal. If the demand is more, the fuel flow is more; if the demand is less, the fuel flow is less.

***Index Terms*— FPGA, Frequency to Voltage Converter, Fuel Flow Control, Stepper Motor.**

INTRODUCTION

A control system is a collection of mechanical and electronic equipment that allows an aircraft to be flown with exceptional precision and reliability.
An aircraft engine is the component of the propulsion system for an aircraft that generates mechanical power. Aircraft engines are almost always either lightweight piston engines or gas turbines.
All aircraft projects involve the design of a fuel system to some degree. The objective of this paper is to explain how we make use of design methods of fuel system in Aero-space engines. Every step in the system development process that can be formalized and automated reduces the time needed from days to minutes or even seconds. Consequently, there is always a room for improvement. The objective is also to minimize the number of errors by helping the designer to understand how flight conditions impact the low-level design parameters. [1]
The modern dual spool turbofan engine used for commercial and military aircraft has evolved into its current form over the past 60 plus years, starting with the first U.S. jet engine, which was built in 1942 by General Electric based on the British Whittle turbojet engine. Controls technology has played a critical role in advancing the performance, reliability, operating life, and safety of modern aircraft engine. An engine control system determines the amount of fuel needed for the engine to produce a desired power (or thrust), based on pilot's power request through a throttle (or a power lever); it then meters the right amount of fuel to the engine's combustion chamber(s); and it maintains the engine power at the desired level in the presence of air flow disturbance and changes in flight conditions. [2]

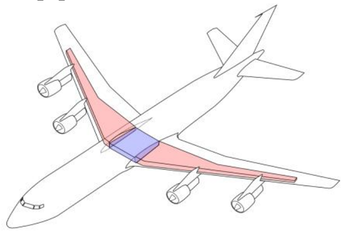


Fig 1.Typical Transport Aircraft Fuel Tank Arrangement

Figure shows the typical fuel tank layout for a commercial aircraft. Wing structure is a common location for fuel storage and in many commercial transports additional tanks are located in the area between the wings. Longer range aircraft and business jets may have tail tanks and/or additional fuselage tanks; however, in most cases the fuselage is primarily the place for passengers, cargo, flight deck (cockpit) and avionics equipment. [3]

The following mechanisms are used in the design of aero engine fuel system:
- Aero Thermo mechanism
- Rotor Dynamics
- Control Systems
- Instrumentation
- Thermal Analysis
- Detail Design of Engine
- Detail Design of Test Bed

Our project mainly focuses on the Control System Mechanism, controlling the fuel flow in the Aero Engine is our main concern in this project. This uses a closed loop control system, as it has many advantages over an open loop control system which is explained in detail in the following pages. Controlling the fuel flow in an aero engine efficiently in every possible aspect is the basic idea of this project.
The scope of the material presented herein is focused on the engine fuel control system covered here at a high level since it is a separate and complex subject in its own right.

PROPOSED SYSYEM

A Closed loop system, also known as a *Feedback control system* is a control system which uses the concept of open loop system as a forward path but has one or more feedback loops or paths between its output and input. The reference to "feedback" simply means that some portion of the output is returned "back" to the input to form part of the systems excitation. Closed loop systems are designed to automatically achieve and maintain the desired output condition by comparing it with the actual condition. The accuracy of the output thus depends on the feedback path. [6]

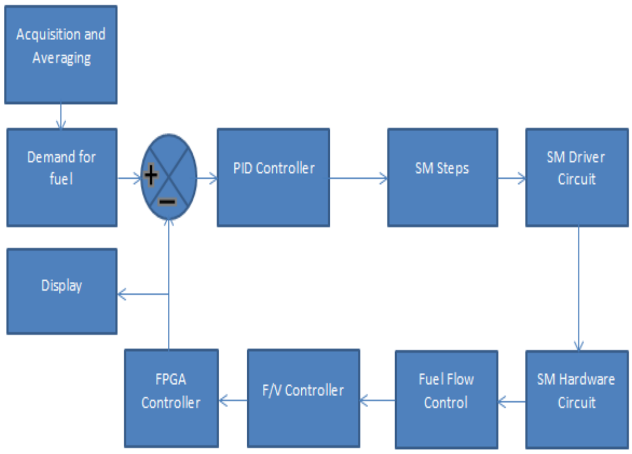
The characteristics of the Closed-loop Control system are:

- To reduce errors by automatically adjusting the system input.
- To improve stability of an unstable system.
- To increase or reduce the system sensitivity.
- To enhance robustness against external disturbances to the process.
- To produce a reliable and repeatable performance.

DESIGN OF FUEL CONTROL SYSTEM

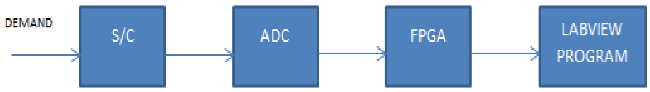
The design of the fuel control system is mainly divided into two phases which is the design of Stepper motor circuit and frequency to voltage (F/V) converter circuit. The block diagram depicts the flow of our project in a very simple and effective manner. The design of each block is complex which involves step by step procedure and provides great attention to the details. These blocks are connected together to control the fuel flow in the aero engine. These blocks are explained in detail below.

Block Diagram:



Acquisition and Averaging:

The pilot sends the demand signals in terms of pressure, BIP or speed. These signals are scrambled and will be varying; as the pilot is in air, take-off or landing mode. These scrambled signals are collected for certain period of time (say 10 samples per second) and then the signals are averaged and the final single input is taken as the demand by the pilot, which is further processed. This is the design of the averaging system. On contrary the data acquisition system is shown below, each signal received by the fuel control system under goes the following process and then the demand is met.



Demand for fuel:

The demand for the fuel is acquired from the acquisition and the averaging system. The accurate signals from the data acquisition system is gathered and sent as a demand for the fuel in various measures such as pressure, BIP (Burner Inlet Pressure) and speed.

PID Controller:

The demand should be met accordingly, but there will be some distortions and variations in the system. This problem can be solved by using PID controllers, which is Proportional, Integral and Derivative. All the three parameters are assigned a constant and added together to remove the variations and distortions in the system. The errors are controlled by removing or adding necessary boosts to the signals. Depending on the demand various constants are assigned to each parameter. [5]

Stepper Motor Design and Control:

The design of the stepper motor involved three main stages.

1. Choosing the right Stepper Motor.
2. Designing the compatible driver circuit.
3. Programming the stepper motor according to the demand.

Step 1: Choosing the right Stepper Motor.

The most commonly used stepper motor in the design of aero engine fuel control system is a Three Phase stepper motor. We choose this because this motor has high system cooling capacity.

Step 2: Designing the compatible driver circuit

The stepper motor needs a driver circuit. The perfect compatible circuit must be designed for power requirements. The design must be simple and effective and also it must be suitable for the microcontroller used in our project. The design should be able to work in high power supply.

Step 3: Programming the stepper motor according to the Demand

The stepper motor must be programmed according to the demand given. We choose LabVIEW software to program the stepper motor for the following main advantages.

LabVIEW gives us the flexibility of a powerful programming language without the complexity of traditional development environments. LabVIEW delivers extensive acquisition, analysis, and presentation capabilities in a single environment. Several LabVIEW characteristics contribute to a significant gain in productivity when compared to other development software.

It uses a simple blocks to design the working of stepper motor in an efficient and easy way. Hence we choose LabVIEW software in our project. The programs are explained in detail in the coming pages. [4]

Frequency to Voltage Converter (F/V):

Frequency to Voltage converter can be used to regulate the amount of liquid or gas flowing through a pipeline. The flow-rate detector generates a pulse train whose frequency is proportional to the rate of flow through it. The F/V converts this frequency to a proportional analog voltage which is used to drive the valve controller. The valve controller regulates the valve so that the flow is steady, even though pipeline pressure goes up and down. A voltmeter connected to the Frequency to Voltage converter output will indicate the actual instantaneous flow rate.

FPGA Controller:
The FPGA (Field Programmable Gate Array) is an integrated circuit designed to be configured by a customer or a designer after manufacturing – hence "field-programmable". FPGAs allow designers to change their designs very late in the design cycle-even after the end product has been manufactured and deployed in the field. In addition, Xilinx FPGAs allow for field upgrades to be completed remotely, eliminating the costs associated with re-designing or manually updating electronic systems.
Here we are using KINTEX-7 FPGA processor;
Kintex-7 FPGAs let designers build in superior bandwidth and 12-bit digitally programmable analog while meeting cost and power requirements. Unprecedented 144GMACS digital signal processor (DSP) power makes the versatile Kintex-7 devices an excellent option for applications such as portable ultrasound equipment and next-generation communications
This FPGA processor is made compatible with the LabVIEW software for programming the desired application part. Thus this Kitex-7 processor helps in building our project in an efficient way to achieve necessary parameters in our project. This is the brief review of our project. [7]

IMPLEMENTATION

Stepper Motor (SM):
Stepper motor is known by its important property to convert a train of input pulses i.e. a square wave pulse into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle. Each rotation is called a step, with an integer number of steps making a full rotation. In this way, the motor can be turned by a precise angle.

Description
The 3 phase stepper motors are extremely robust, maintenance free drives. They carry out step by step movements which are controlled by a positioning controller. The 3 phase stepper motors can be operated at very high resolutions with appropriate control electronics. Options such as rotation monitoring and holding brake with robust, low play, planetary gear extends the application options.

Features
The 3 phase stepper motors are:
Powerful, the optimized internal geometry of the motor offers a high power density i.e. up to 50% greater torque as compared to conventional stepper motors of comparable size.
Silent, the sine communication of the drive and the special mechanical design result in a very quiet and virtually resonance-free stepper motor.
Versatile, with a flexible modular system and modern variant management, a wide variety of motor types can be manufactured and delivered in a very short time.
Implementation:
Major concern of using a stepper motor is to control the fuel supply and hence the control of engine parameters, i.e. frequency, RPM etc. for implementing a fuel control and simulator for engine control stepper motor study is very important. Following implementation details are discussed here

- Stepper motor position and connection
- Stepper motor specifications
- Finding the rotations

SM position and connections: Stepper motor is placed inside the fuel pump of the engine. Fuel pump of the engine receives the fuel from fuel inlet and which is pumped from a low pressure to high pressure.
Stepper motor rotating axis is connected a moving plate which covers the fuel inlet. This moving plate is known as "camplate". When stepper motor is rotating in a clockwise direction camplate moves in a forward direction and vice versa. So opening and closing of the inlet depends on the direction of the stepper motor.
Direction of the stepper motor depends upon signal it is receiving from the stepper motor drive circuit. Dependence of the direction of SM on drive circuit will be explained in the next part. And this drive circuit receives the command from a microcontroller which is in the processor of ECU. This controller takes the command from the pilot and compares it with the present values and gives command to the SM to either vary or to maintain a fuel supply. This gives the main implementation of the engine control.

SM Specification:
Stepper motor used here is a 3-phase stepper motor. General structure of winding inside this SM can be shown as:

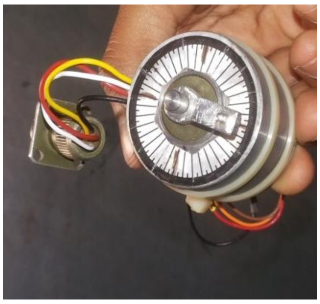


Fig 2. Three Phase Stepper Motor

The output voltage of this driver circuit is 3.3V. But for the FPGA to detect this signal is quite impossible since it needs much stronger signal for its proper working. Hence we design a driver circuit which gives around 28V as the output of this stepper motor
A rough sketch of SM drive circuit and SM as loads can be shown as

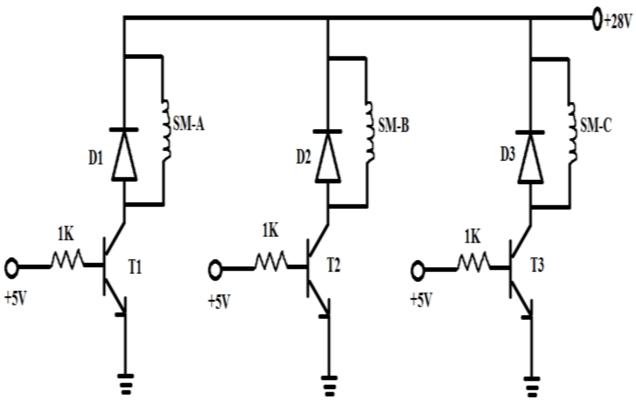


Fig 3. Stepper Motor Driver circuit

The circuit details are explained below:

- We have used the TIP-122 transistors for driving the circuit, since they withstand high power loads.
- This transistor is driven by giving the base voltage of 5V
- The stepper motor connections are given to the collector and the emitter is grounded.
- The three phases A, B and C are connected to SM-A, SM-B and SM-C as shown in the figure.
- This circuit gives 28V as the output. This is easily detected by the FPGA.

Stepper motor can be operated in 2 modes, clockwise and counter clockwise.

Mode 1: Clockwise direction
The camplate moves in direction such that it increases the fuel supply which results in the increase of the frequency of engine.

Mode 2: Counter Clockwise direction
The camplate moves in direction such that it decreases the fuel supply which results in the decrease of the frequency of engine. By deciding the direction of stepper motor fuel supply can be varied accordingly.
The table shows the sequence of the stepper motor in forward and reverse directions.

Table 1:

A	B	C	STEP
1	0	0	4
1	1	0	6
0	1	0	2
0	1	1	3
0	0	1	1
1	0	1	5

STATUS BIT DIAGRAM FOR CLOCKWISE DIRECTION

Table 2:

A	B	C	STEP
1	0	1	5
0	0	1	1
0	1	1	3
0	1	0	2
1	1	0	6
1	0	0	4

STATUS BIT DIAGRAM FOR COUNTER CLOCKWISE DIRECTION

Then stepper motor rotates in counter clockwise direction. Thus the direction of rotation of stepper motor is determined by the status bits. The program for this is explained later.
The stepper motor can withstand load up to 300kg N and maximum current capacity is 1A. The stepper motor used here first resets to 250 steps and then moves forward according to the feedback obtained, if the feedback is positive the stepper motor moves in forward direction; if the feedback is negative the stepper motor moves in reverse direction.
1 step = 0.8^{o}
The stepper motor maximum time consumption between each step is around 10msec, we have designed for this time limit.
The RPM of the engine is found using the equation,

RPM = Number of cycles * 60 / Number of teeth

FREQUENCY TO VOLTAGE CONVERTER (F/V):

A converter that provides an analog output voltage which is proportional to the frequency or repetition rate of the input signal is derived from a flow meter, tachometer, or other alternating-current generating device. It is abbreviated as F/V converter.
Every system must have a controlling unit; this stepper motor governing unit is the F/V converter. The output of the stepper motor is usually frequency signals, these signals are monitored by this converter. The converter's input is frequency signals of the stepper motor. These signals are converted to voltage and given as feedback to the main circuit. The IC used in this circuit is LM2907/LM2917. These IC's help in the conversion of frequency to voltage signals.

Description of LM2907/LM2917:
The design of this circuit involves complex equations and analysis which are given in the data sheet attached with this report in the end. The usage, advantages and the disadvantages of this IC everything is mentioned in the data sheets. The circuit which we designed is shown below, this is the exact circuit which helped us to control the fuel flow in the aero engine. This circuit is designed for minimum external part count applications and maximum versatility [8].

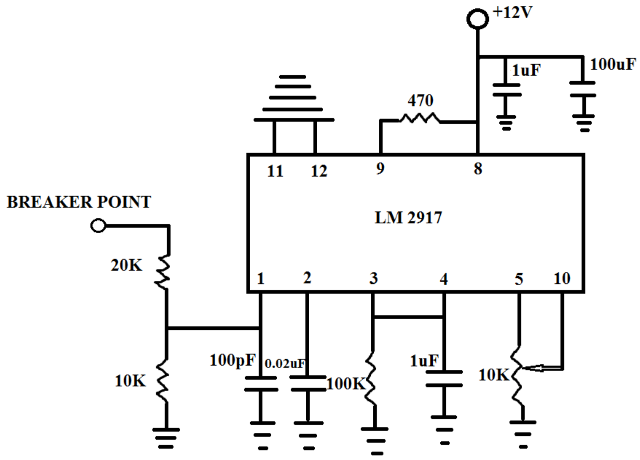


Fig 4. F/V Driver Circuit

Design of the Circuit:
$dQ/t = i_{c(avg)} = Vcc * f_{in} * C_1$ (1)
Consider,
$Vcc = 5V; f_{in} = 80hz; i_{c(avg)} = 50mA$
Substituting the above values in (1)
We get,
$C_1 = 125uF$; but we choose 100uF.
$Vo = Vcc * f_{in} * C_1 * R_1 * K$ (2)
We have,
$Vo = 10V; K = 1$ (constant)
Substituting the above values in (2)

We get,
R_1 = 250 ohm; but we choose 470 ohm.

Applications:
The frequency to voltage converter can be used for any application that requires measurement of a repeating event, such as a wheel making a complete rotation. For the robot, this could be used in place of the current encoders to measure velocity.

PROGRAM DESCRIPTION

The stepper motor program is designed as shown below using LabVIEW software.
The program has mainly two cases:

- Resetting the Stepper Motor
- Forward and Reverse rotation of Stepper Motor

Resetting the Stepper Motor:
The stepper motor first resets to 250 steps and then the demand is met according to the signals acquired by the acquisition system, the stepper motor sequence is given to index array where single step sequence is monitored, then the steps are given to the three phases of the stepper motor.

The stepper motor has six main steps which are in the following order:

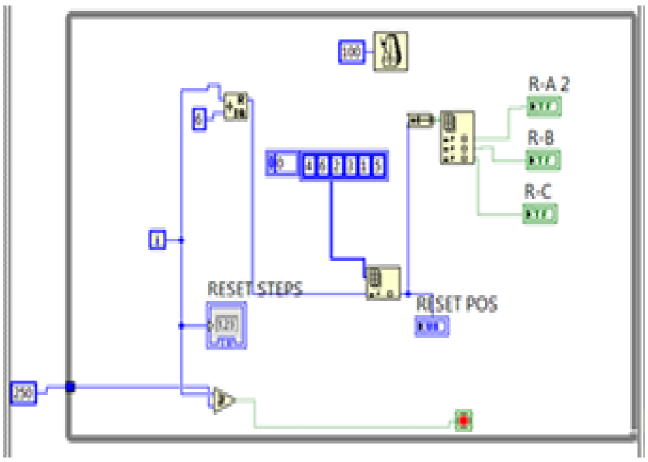


Fig 5. Program for Resetting the Stepper Motor

Forward and Reverse Rotation:
The sequence is 4, 6, 2, 3, 1, and 5. When the demand is positive the stepper motor rotates in forward direction and moves according to the sequence mentioned above.
The sequence is 5, 2, 1, 3, 6, and 4. When the demand is negative the stepper motor rotates in reverse direction and moves according to the sequence mentioned above.
The demand here is met according to the signals acquired by the acquisition system, the original stepper motor sequence is first reversed and then the steps are given to the three phases of the stepper motor so that the stepper motor rotates in reverse direction.

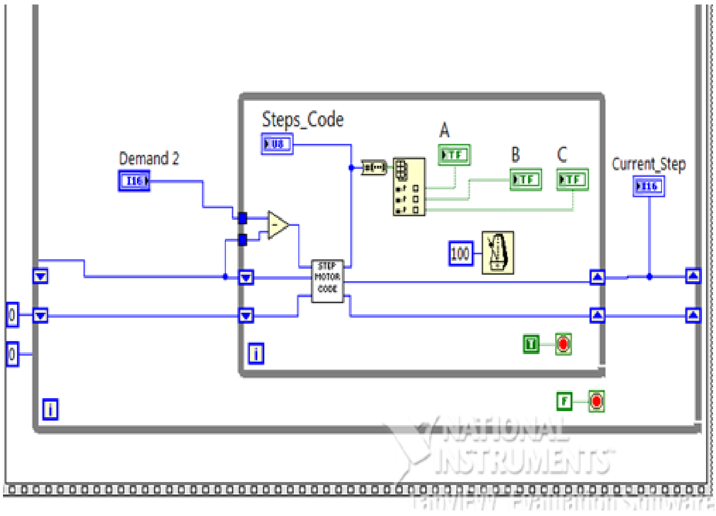


Fig 6. Program for the Rotations of Stepper Motor

The Front Panel of the above program is shown below.

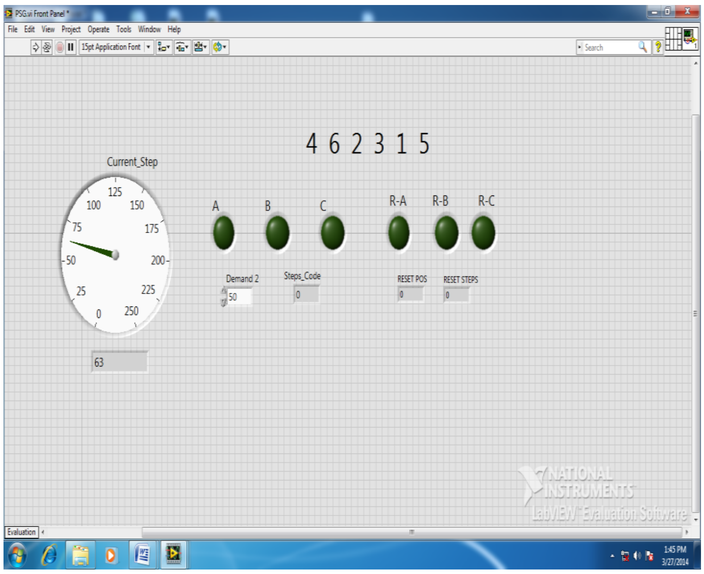


Fig 7. Program showing the Front Panel of Stepper Motor

R-A, R-B and R-C are the reset steps.
A, B and C are the three phases of the stepper motor.
The dial shows the stepping sequence of the stepper motor.

ADVANTAGES

- Efficient monitoring & control system
- Real time transfer of data which helps in monitoring the parameters constantly & accurately
- Cost effective
- Time efficient
- Easy to construct & install
- Consumes less energy
- Increase the overall efficiency of the system
- Works at high speed
- These systems there was no control unit, person present in the earth station use to guide the movement of an aircraft to the pilot, hence control systems are used in order to avoid limitation.

APPLICATION

- Used for defence aircrafts
- Used in civilian aircrafts
- Used in marine applications
- Same concept to other automobiles

OBSERVATION AND RESULT

The demand here is the Throttle Demand which is commanded from Ground Control Panel. It can be varied from 0 to 10 volts. The demand is compared with the feedback and the resultant output is seen in the metered flow and spill flow. Depending upon the demand value the stepper motor will rotate.

Our observation involves mainly two steps i.e., the Demand and the Fuel Flow.

Demand:

- The demand is given mainly by the pilot through the throttle, depending upon the speed required to maintain in the free space (usually air).
- The demand is first acquired and then sensed.
- This demand is signal conditioned and sent to the stepper motor driver circuit.
- The stepper motor initially resets to 250 steps and then moves forward if the demand is positive or moves backward if the demand is negative.
- These movements are mainly observed in the software system and the demand meet is observed in the fuel flow meter.
- Since our design is based on closed loop we have to consider the feedback and the error that the feedback produces while meeting the demand.
- The demand signal and the feedback signal must be approximately equal which shows that the demand is meeting the feedback.
- When the demand and feedback signal are equal the meter reading comes to halt which shows that the error at that particular point is zero.
- This demand governs the stepper motor and the stepper motor rotates based on these conditions and the fuel flow from the fuel tank is made to flow depending upon the speed required.

Fuel Flow:

- The fuel demanded is made to flow in the metered flow pipe.
- The subsidiary fuel is made to flow in the spill flow pipe.
- As the demand is increased, the fuel flow in the metered pipe is more whereas the flow in the spill pipe is less.
- On the contrary, if the demand is decreased, the fuel flow in the metered pipe is less and the fuel flow in the spill pipe is more.
- The fuel in the spill flow pipe is given back to the fuel tank and this fuel is reused without any wastage.

Result:

The following graph shows the result for certain values of the demand,

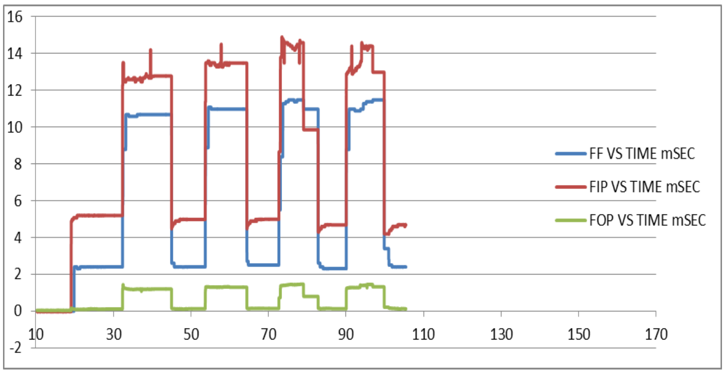


Fig 8. Graph which shows the overall Result

The blue graph indicates the FF- Fuel Flow
The red graph indicates the FIP- Fuel Inlet Pressure
The green graph indicates the FOP- Fuel Outlet Pressure
The first two graphs show the output of closed loop system, the next two graphs show the output of Open loop system.

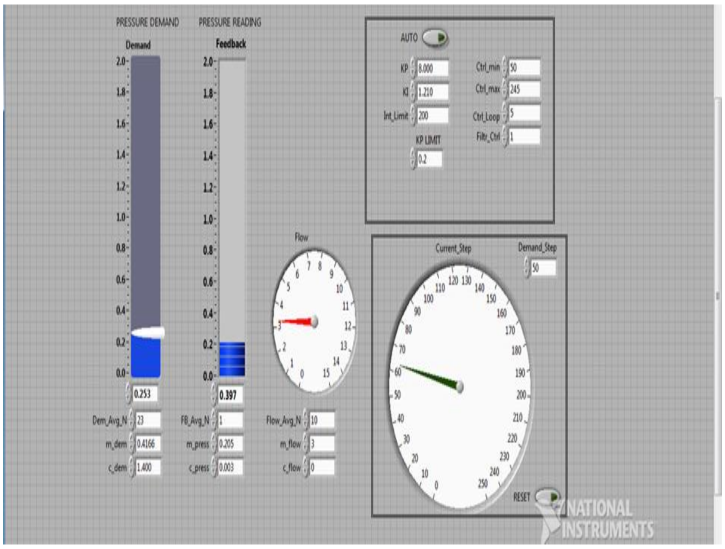


Fig 9. The Main Driving Program

The above diagram depicts the final output of the FPGA where the Demand and the Feedback will be almost same. Various parameters such as PID Controller Constants, Flow Meter, and Stepper motor Current Loop is shown.

CONCLUSION

The proposed project named "Closed Loop Fuel Control of Aero Engine" focuses on the control of the fuel flow with respect to the engine speed. Modern engines are typically controlled using a Full Authority Digital Engine Control (FADEC) system. Various sensors and actuators interfaces to the ECU using a mixture of analog, discrete and digital interfaces. Hydro mechanical components provide fuel pumping and metering and various other actuation systems are also used. The decision on what amount of fuel has to be injected to the engine is taken based on the feedback obtained from the gas turbine engine, whose temperature, pressure are again measured using the sensors. The limiters i.e. the maximum temperature and pressure beyond which the aircraft wouldn't withstand, when given as the feedback, the fuel flow will reduce regardless of the speed with which the aircraft is moving. Hence our proposed project which includes the integration of control systems with the aircraft provides reuse of the system and software designs between applications.

There are number of generally accepted stages in the design, development, manufacture and operation of aircraft, each with associated design methods and data requirements. The possibility of lowering the cost of fuel control systems for gas turbine engines is high and the main areas of research have also been determined regarding this. In general the modern electric/electronic technology will be employed since there is no doubt that such systems will prevail in the future.

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