Design and Development of Jet Engine Testing Training Simulator

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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ABSTRACT

Training simulators are used in a variety of industries that require the skill of handling complex or sophisticated technologies and having knowledge of advanced controls. Training simulators have a long history; a number of studies have already been done to make the training simulators more flexible.

Jet engine testing operators have to follow a proper methodology to carry out the procedures of safe engine testing. While performing the tests, the operators have to deal with various emergency conditions and should have proper information on how to deal with those situations. This thesis presents the design and development of a training simulator for aviation engine testing operators. Engine simulation software, GasTurb, is used to develop the jet engine model files and to get the output variables from the simulator. These model files are made accessible in Simulink (MATLAB) with the help of second order S-function. The S-function accesses the Dynamic Link Library (DLL) of GasTurb, to read the model files and to provide real time output on the basis of inputs from external hardware. The user interface to display these output values is developed in Unity game engine. Five different emergency scenarios have been designed and evaluated using the developed simulator.

Related variables for these emergency scenarios are plotted to compare the reaction of the operators. The feedback is also taken from the operators regarding the effectiveness of training simulator. The result shows that training simulator would promote and develop their understanding of process. It would help to enhance the ability of operator to identify parameters causing the emergency scenarios and enable them to overcome such situations.

ACKNOWLEDGMENT

It is a privilege to express my deep sense of gratitude and indebtedness to the person who has been most instrumental in this dissertation, my supervisor and guide Dr. Nariman Sepehri. Had it not been his show of immense confidence and faith in me, I would never have been able to finish my dissertation. I am thankful to him for his persistent encouragement, constructive criticism and incomparable guidance.

I owe my special debt of gratitude and heartful thanks to StandardAero and GE aviation representatives, for technical support and assistance. Their constructive suggestions and valuable advice are duly acknowledged. I am very much thankful to Kathryn Atamanchuk for her timely support and guidance. I am grateful to Mr. Vikram Banthia, Mr. Ahmed Imam, Mr. Ali Maddahi, Mr. Khurram Butt and other lab members for their help and valuable suggestions and for creating a conducive environment. The labours put forward and cooperation given by the laboratory assistant Mr. Ehsan Jalayeri is highly appreciated.

I acknowledge with thanks the help, inspiration and cheerful company of my friends Rajbir Kaur, Harshita Chaudhary and Nitish Sem. I am also thankful to all those who stood by me in the need of hour without which it would have been hard to complete this project. I fall short of words to describe the depth of gratitude towards my parents and my brother Gaganpreet Singh to whom I owe everything. Without their blessings this work could not have taken material form.

Last but not the least I thank the almighty for giving me strength to carry out my work with sincerity and honesty, and hope to carry this on in future.

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1 INTRODUCTION

Air travel is considered to be the fastest and least dangerous way to get to the destination [1]. Much of the credit for making air travel reliable goes to the modern techniques of testing the jet engines. The emphasis on proper training ensures that skillful operators are available for the testing of engines. The importance of having well-trained and competent operators for safe and correct operation of equipment is well-established. The training of operators for the testing of jet engines proved to be a challenging task for the aviation industry. Every year a significant amount of money is spent to train the new operators capable of testing the engines [2]. Training of novice operators on real engine leads to various difficulties such as no constant availability of the real engine for testing and also the required weather conditions are not accessible throughout the year. Moreover, using actual equipment for training novice operators is not recommended due to potential damage to the equipment, unavailability of the equipment, cost of operation and maintenance. In order to ensure that effective training has been provided to the operators, it has become extremely important to develop the training simulators. Training of operators using a simulator involves no risks and operators can make considerable mistakes, which only add to their learning experience. It is cost effective to operate simulators as compared to operating real machines. Simulators can run continuously and can be initialized to any operating mode. It is also easier to set and record performance indices using simulators to study training progress. Nevertheless, good training must maintain a balance between the use of simulators and actual equipment.

In the present study, a training simulator has been developed that would imitate the engine testing facility and it provides a graphical user interface for analysis of engine behavior during testing. A flexible engine model has been engineered for the simulator which is capable of accessing signals from external hardware and generates output in real time. Actual equipment such as throttle lever and control panel has been used in the simulator. Interestingly, the simulator is capable of introducing emergency scenarios while training the operators; this would help the operators to learn the procedure of tackling emergency situations to avoid the engine damage.

1.1 PROBLEM STATEMENT

1.1.1 MOTIVATION AND PROBLEM DEFINITION

According to Federal Aviation Administration (FAA) Aviation Safety Information Analysis and Sharing (ASIAS) analysis, 1,740 out of 8,657 aviation accidents which occurred between 2003 to 2007 were mainly due to weather conditions [3]. Besides weather conditions, many plane crashes have been reported due to BASH (Bird Aircraft Strike Hazard) or bird strike. According to Richardson & West [4], bird strike has resulted in the loss of 283 aircrafts and 141 deaths between 1959 and 1999. To avoid such accidents, there are many engine testing facilities built across the globe which tests the endurance and reliability of jet engines under extreme weather conditions. To make the air travel safer, several pre-flight tests have been designed for the jet engines, such as bird ingestion test, cold water test and ice ball test for which a simulated environment is created at engine testing facilities [5].

According to Federal Aviation Regulations, an aircraft is not certified to fly unless it clears the Icing certification [6]. Icing certification is one of FAA's aircraft certification in which the performance of jet engines is tested under extreme cold weather conditions. Each year test facilities spend large expenditures to create simulated conditions for cold weather [2].

In these facilities, the availability of engines for testing is not possible throughout the year. Moreover, the temperature that is required for the testing of the engines should be around -8°F [7]. Therefore, engine testing and training is possible only for four to five months. Hence, it is a big challenge for the facilities to keep their operators engaged in the practice throughout the year and train more operators for testing engines.

Operators are required to be well trained to perform testing of jet-engines. Lack of experience and competency while testing can be hazardous and can results in loss of life as well as damage of jet-engines. There are several incidents in the past where error committed by operator led to fatal accidents. In 2008, an accident occurred due to the violation of test procedures by an operator of Etihad airways in UAE [8]. In 2011, another incident took place in New Zealand where a maintenance engineer was pulled into the fan by thrust of the jet engine while testing [9].

To overcome these challenges and to refrain such unfortunate incidents that happened over in past, extensive study is required that can propel effectual training to the operators in a safe and cost-effective manner.

1.1.2 PROPOSED SOLUTION

The Literature reveals that a testing facility faces several problems such as availability of training equipment throughout the year, adequate testing conditions as well as high cost involved in the training process while testing the engines and training the operators. In the current study, an effective training simulator is proposed for testing facilities to fill the gap in the existing training methods. The training simulator is having four-fold advantage:

i. It is safe and less expensive to train operators on simulator than on real equipment. It eliminates the risk of damage to sophisticated controls and apparatus.

ii. It facilitates the training of operators throughout the year. It does not need any specific conditions or environment to run a training simulator.

iii. The operators can be easily trained to face the emergency scenarios which are not possible on real equipment.

iv. It is easy to make changes in the training simulator with the change in technology. It doesn't involve the cost of changing the overall training setups which turns out to be expensive.

1.2 THESIS OBJECTIVE

The objective of the present research is to develop a training simulator for jet engine testing. The simulator must facilitate the training of novice operators and at the same time, it should evaluate the performance of experienced operators to test the jet engines. The following requirements need to be accomplished to fulfill the objective of this research:

i. In order to imitate the engine testing facility, simulator is required to use the actual equipment such as throttle lever and control panel. The throttle lever controls the fuel flow whereas the control panel facilitates the start and shut down of the jet engine.

ii. Simulator should provide a graphical user-interface to display the values of various variable for analysis of engine behavior during testing.

iii. Another major requirement is to innovate a method that allows developing a flexible engine model for the simulator. Engine model should be capable of accessing signals from external hardware and generate outputs in real-time.

iv. Simulator should have the ability to introduce various emergency scenarios for the training of operators. By introducing emergency scenarios, simulator can train the operators to tackle the conditions that can lead to engine damage.

v. The simulator should allow the trainers to evaluate the performance of operators based upon the execution of engine testing plans and their reactions to emergency situations.

1.3 THESIS OUTLINE

Chapter 2 discusses the relevant literature review in accordance to the focus of this thesis. It covers the basics of Jet engines and it gives an overview of the testing simulators in various industries and how is it helpful for them.

Chapter 3 covers the methodology followed to develop the training simulator. It covers the issues which were to be overcome while designing the simulator. It also provides the information of all the hardware and software used for the development of this training simulator. Emergency scenarios which were designed for the operators were also discussed in this chapter.

Chapter 4 describes the tests that were carried out by the operators to evaluate their performance. It also discusses the procedures to be followed by the operators to perform these tests.

Chapter 5 explains the contribution of this research and directions for future work.

2 BACKGROUND LITERATURE

2.1 INTRODUCTION

The origin of simulators industry is attributed to the use of flight training devices. In the history of training simulators, the first simulator was developed in 1910 for the training of flight pilots [10]. Continuous efforts have been made in the simulation industry to gain recognition for its use, the constant demands of matching ever increasing technology and the establishment of standards. Owing to the contribution of flight simulator in the field of aviation, researchers have realized the need for developing training simulators in other fields such as construction, teaching, process industries and medical applications. This chapter covers the fundamentals of Jet engines for GasTurb model design and literature review of training simulators.

2.2 FUNDAMENTALS OF JET ENGINES OPERATION

Jet Engine is the aircraft propulsion application of Gas Turbine. In jet engines, the thrust is generated by accelerating a mass of fluid in the opposite direction to air craft motion. It propels the aircraft in the forward direction. In Jet engines, the fan installed at the front draws in the air and after that compressor increases the pressure as well as temperature of air as shown in Figure 2-1. The compressor is made up of fans having many blades and attached to a shaft. The exit diffuser of the compressor passes air to the combustor. Compressed air is then mixed with fuel and burnt, which raises the temperature of the exit gas. This gas expands in the nozzle and blasts out from the back of engine. This further results in the forward thrust [11].

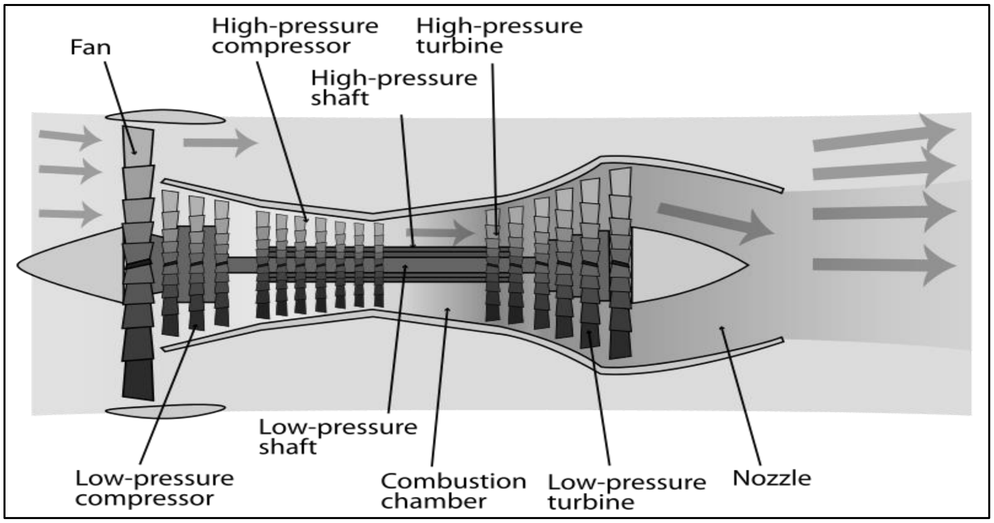

Figure 2-1 Components of jet engine [12]

Jet Engine works on the principle of Brayton cycle. The working fluid is air which undergoes combustion and exhaust processes. This is considered to be heat addition and rejection with constant pressure. Brayton cycle consists of 4 reversible processes (see Figure 2-2). Process 1-2 is isentropic compression in the compressor; process 2-3 is constant pressure heat addition in the combustion chamber; process 3-4 is isentropic expansion in the turbine and 4-1 is constant pressure heat rejection at exhaust.

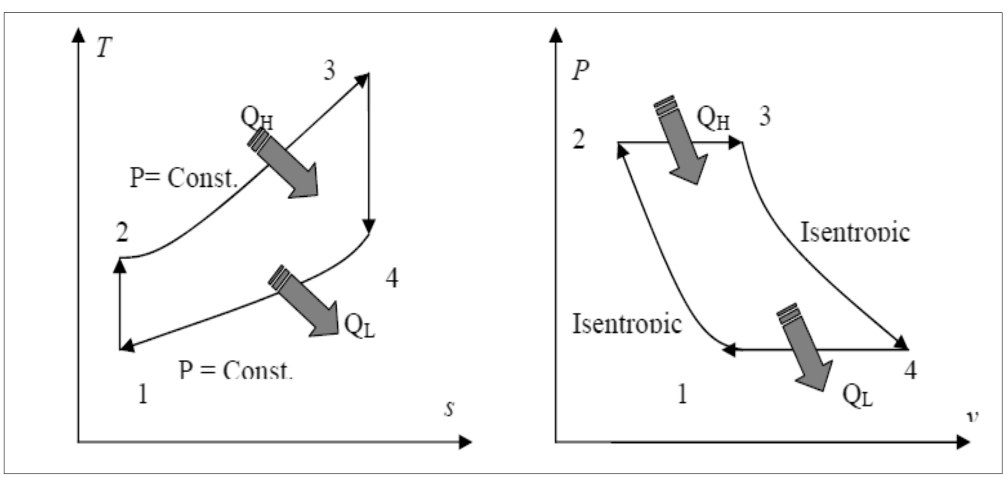

Figure 2-2 T-s (temperature entropy) and P-v (pressure volume) diagrams for ideal Brayton cycle

2.2.1 COMPONENTS OF JET ENGINE

Jet engines mainly consist of a fan, compressor, combustor, turbine and nozzle as shown in Figure 2-1.

2.2.1.1 FAN

The fan is the first component of the engine which spins and draws a large quantity of air. The fan is mainly made of titanium. The air gets divided into two halves. One half goes through the core of the engine where it passes through the compressor, combustor and turbine. The other half goes from the outer duct of the engine, as shown in Figure 2-1. This is known as the 'bypass' duct which covers the compressor, combustor and turbine of engine. After flowing through the bypass duct, this cold air mixes with the hot air from the core of the engine in the nozzle and produces the thrust for the plane.

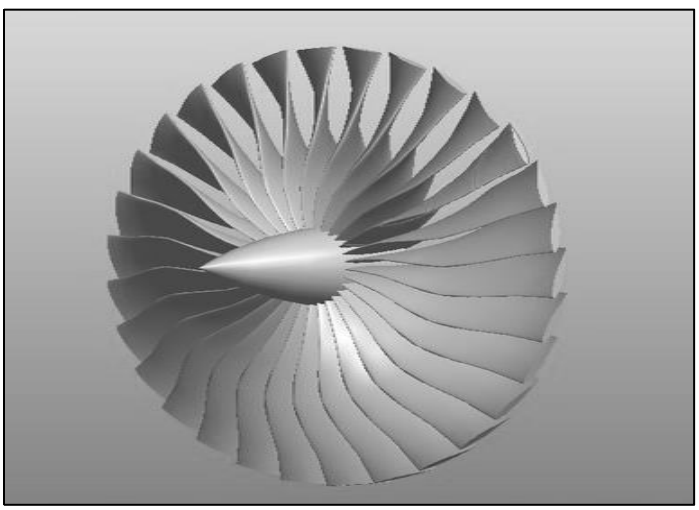

Figure 2-3 Fan of jet engine

2.2.1.2 COMPRESSOR

After the fan, the air enters the compressor. Every jet engine has a compressor to increase the pressure of the air. Jet engines mainly have only two types of compressors, axial compressor and centrifugal compressor. In the most common jet engines i.e. two spool turbofan engines, there are two compressors present. One is low pressure compressor, which is just beside the Fan and the other is a high pressure compressor which is present after the low pressure compressor. A high pressure compressor and high pressure turbine are connected with one shaft, whereas a low pressure turbine, low pressure compressor and fan are connected to another shaft in a two spool turbofan.

Figure 2-4 Compressor of jet engine

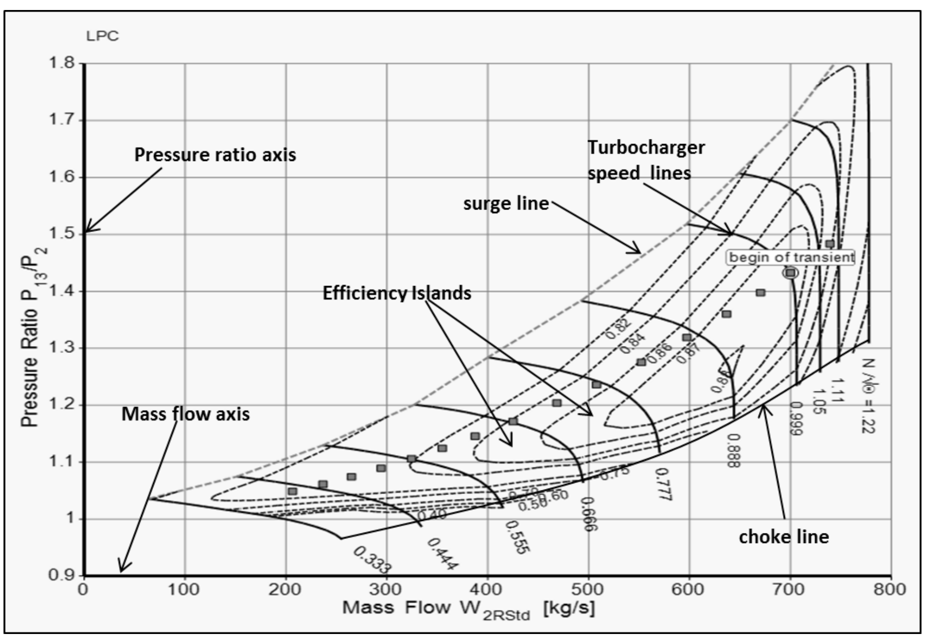

Figure 2-5 Compressor map

The compressor's performance is decided by the compressor map on which it works. The compressor map has a mass flow axis as x-axis and pressure ratio as y-axis. The left hand boundary of the map is known as the surge line and the right hand boundary is the choke line. There are concentric circles in the graph which are the efficiency islands and the lines intersecting these islands are turbo speed lines, as shown in the Figure 2-5.

2.2.1.3 COMBUSTOR

In the combustor, the fuel is mixed with the air and ignited to increase the temperature of the air. Higher temperature increases the energy of the airflow. The fuel then burns with the air and produces hot expanding gases. The combustor is mainly of ceramic material to make it heat resistant, as the temperature can reach 2700°C.

2.2.1.4 TURBINE

High energy airflow from the combustor enters the turbine. It results in the rotation of turbine blades. The turbine is linked to the compressor and fan with a shaft. Some energy is consumed by the rotation of compressor and fan. In two spool turbofan engines, there are two turbines: a low pressure turbine and high pressure turbine. The high pressure turbine rotates the high pressure compressor and the low pressure turbine rotates the low pressure compressor and fan.

2.2.1.5 NOZZLE

The nozzle is the exhaust of the engine. In this part of the engine, the cold air from the bypass and hot air from core mixes together and generates thrust, which propels the engine. The combination of hot and cold air results in high energy exhaust and it also helps to make the engine quieter. This is also known as mixer of engine.

2.2.2 TYPES OF JET ENGINES

The most basic jet engine is the turbojet engine (Figure 2-6) which comprises of inlet, compressor, combustor, turbine and nozzle. There are also afterburner turbojets, which includes the second combustor. The second combustor helps to increase the thrust of the engine, but it significantly decreases the efficiency of the turbojet engine. So the afterburner is implemented only when the maximum thrust from the engine is required.

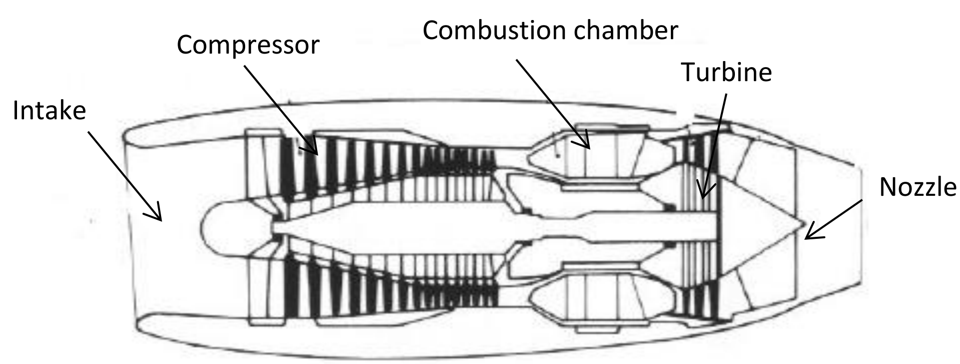

Figure 2-6 Turbojet engine

There is one more type of modern jet engine which is called turbofans (Figure 2-7). Turbofans are more efficient than the turbojet engines and they are having one extra cowling around known as the bypass duct. It consists of a fan in front which compresses the air. Some of the air from the fan enters the high pressure compressor, whereas most of the air passes from the outer cowling known as the bypass duct. The compressor, combustor, turbine and nozzle collectively comprise the engine's core. The amount of air passing through the bypass duct and engine's core is decided by the bypass ratio (BPR). Bypass ratio is the ratio of airflow from bypass duct and engine core respectively. The air from the bypass duct also passes through the nozzle to produce thrust.

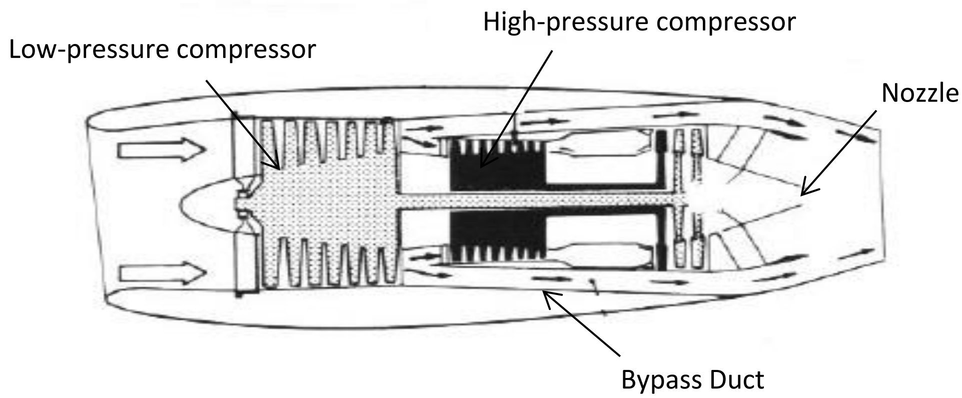

Figure 2-7 Turbofan engine

In afterburning turbofan engines, the air from the bypass duct mixes with the core engine's combustion product and fuel. This is combusted just before the nozzle to produce high thrust. Afterburners in turbofans are only used during take-off or when high thrust is required for a shorter period of time, due to fuel consideration. Military fighter aircraft are equipped only with afterburner turbofan engine with low BPR. Commercial aircraft are equipped with High BPR turbofan engines, as they are more efficient. Due to high BPR, the bypass duct size increases, which ultimately increases the size of the turbofan engine and makes them bigger with a big fan in front to handle more air.

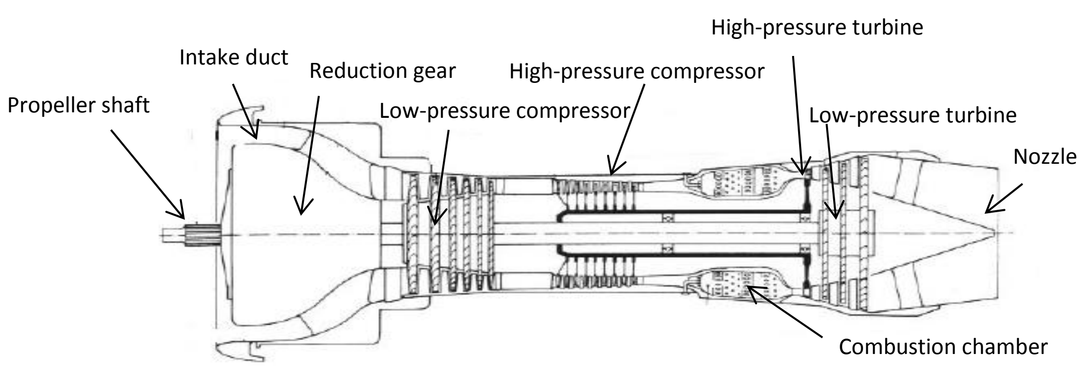

Figure 2-8 Turboprop engine

Turboprop engine (Figure 2-8) and turboshaft engine are also based on the Brayton cycle, with little variation. In these engines the core is similar as in a turbofan. Additionally, these engines have low pressure turbine which are used to rotate a propeller or helicopter rotor. It is not connected to a compressor or fan. It consumes most of the energy of combustion products after they leave the core. These engines don't have any duct around, but do have a nozzle following the low pressure turbine. Since, most of the energy is extracted by a low pressure turbine to run the propeller; the nozzle which is left, comparatively produces less thrust. Thus, the main propulsive effect is only achieved by rotor or propeller. To provide appropriate rpm for the propeller, rotor and other engine parts, these engines are employed with highly efficient gear box.

2.3 SIMULATORS FOR TRAINING

The scope of simulator based training has expanded with the improvement in simulator technology. Today simulator based training includes basic system procedures, emergency procedures and flight transitions [13]. An Operator Training Simulator (OTS) is a virtual device used to train operators either for operating machines or for running processes and performing different procedures. There are many applications of the OTS in the fields of navigating planes and ships, military training and to perform medical surgeries. An OTS works on the basis of a mathematical model developed to mirror the procedure of the technical system for which training is to be provided. An OTS mostly has an interface with which the trainee interacts to the virtual environment through emulated controllers. This helps the operators to change the controller settings and visualize the changes in the process and helps to solve different technical problems [14].

2.3.1 SIMULATOR TRAINING IN CONSTRUCTION INDUSTRY

In the construction industry, simulators are used to analyze various issues such as operator trainings, engineering problems, and logistics of heavy machines [15]. The concerns like human failures, weather conditions and absence of health and safety aspects can lead to serious consequence in the construction industry [16]. Thus, it is important to capture and replicate the real world events using simulators to train the operators for these situations at construction sites.

The construction industry is one of the high-risk industries [17] and most of the accidents that take place are because of the mistakes done by operators in handling the large mobile cranes or tower cranes [18]. Improper or insufficient safety training is considered to be the major cause of these accidents [19]. Therefore, the main perspective of the operator training simulator in construction industry is to foster direct and subjective learning which is close to the reality and helps to retain the information. Chi *et.al* [20] shows that training with the simulators is effective for the operators to use heavy equipment in the construction industry.

Figure 2-9 Three screen projection training simulator [21]

In 2010, Tichon *et.al* [21] proved with a case study in her review article that the civil construction industry novice operators can be trained with the training simulators, as shown in Figure 2-9. It helps them to gain the skills for safe working environment and also it will help the construction industry to meet its manpower demands. It helps the operators to get the training of risky construction projects without getting into a precarious situation.

On job training is considered to be expensive in the construction industry and it does not provide an actual experience. There is always risk at the construction site for the novice operator. In 2012, Goulding *et.al* [22] proposed the simulator training for on job trainees in the safe environment named as offsite production. Their main proposal was to make trainees learn how to react in emergency situations and to make them understand the consequences of the emergencies. The main concern was that the prototype made using the data was applicable for only one particular problem, which may constraint them from getting enough results. Therefore, while developing a training simulator, this is to be kept in mind that it has to be flexible enough to generate various scenarios. It should be versatile enough to train the operators under various situations and should help them to cover each part of their training process.

In 2009, Panagiotis *et.al* [23] explained in his conference paper the advantages and challenges for the use of the Manu Build construction site training simulator. These types of simulators and advanced learning techniques help the operators in the learning process and it further helps to enhance the businesses. Success stories of DELL and IBM are recorded about how simulators and advance learning techniques help them to grow and meet the industry demands of skillful workers [24]. These simulators allow the operators and trainees to give feedback responses, reflex actions and real time involvement in different scenarios which help them to learn things as per they are designed [25], [26].

2.3.2 SIMULATOR TRAINING IN PROCESS INDUSTRY

In the process industry, there is always a demand for skillful workers. It is considered that the conventional methods of training are insufficient to train operators for the seldom occurring hazardous events [27]. Chemical companies are using training simulator to train their staff to handle different various failures of machines. Some of the other applications of training simulators in process industries include assessing the skills of operators in exploring the new mechanisms and to perform safety tests without affecting the real systems [28].

In last 30 years, 28% of the accidents in the process industry occurred due to operational errors [29]. Yang et.al [29] suggested using Dynamic Operator training simulator (DOTS) in 2001 to create realistic plant like emergency situations. This simulator works on the principle of dynamic modelling and has an inbuilt package to evaluate the performance of the operators, stating the areas to be improved.

In 2011, Brambilla *et.al* [30] described the features of the accident simulator in a chemical industry, so that the operators and workers can be trained to face the emergency conditions to do the risk assessment of those emergency conditions. It also simulates the flow of different liquids and chemicals during the fire outbreak to train the operators that how to react when particular type of fluid leads to disaster.

Park *et.al* [31] suggested the human reliability analysis with the help of a simulator to deal with the emergencies in a nuclear plant. In their study, they collected the data of the human performance in emergency situations and how they cope with those situations with the help of simulator and later on it was analyzed to design better safety features and to enhance the safety of the workers of nuclear plant.

In 2014, Balaton *et.al* [32] reported that the operator training simulators (OTSs) are of great use in chemical industries to train the skilled workers for the severe and complex processes. Use of OTSs is economically more beneficial and it provides a safe environment for higher productivity. His main concern was that the OTS should be capable enough to replicate the real situations. He has discussed various parameters affecting the thermal and hydrodynamic behavior of jacketed batch of nuclear reactor.

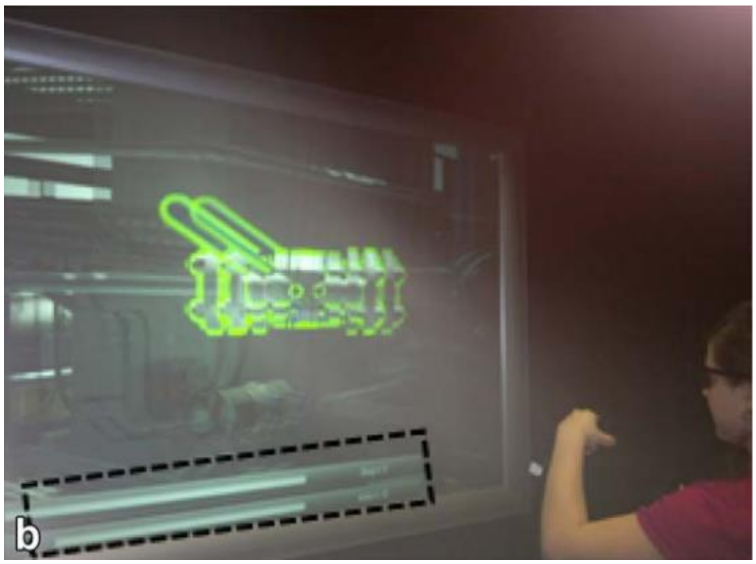

Figure 2-10 Plant simulator [33]

Nazir *et.al* [33] suggested the implementation of a tool called Plant Simulator (PS) to make operators experiencing the different scenarios of real plant operations. It was concluded that the training with a plant simulator as shown in Figure 2-10, make the operators more efficient with industrial safety and it also help operators in improving their performance, receptivity and skills to perform various tasks.

With the advancement in the technology in the process industry; the training of the operators is important. To keep the operators updated with the advanced technology and providing them with proper skills has become one of the main priorities of process industry. Dudley *et.al*

[34] discussed the operator training simulator for the pebble bed modular reactor plant which is a one of its kind high temperature reactor. Due to the advancement in the control systems of nuclear power plants, it is necessary that there should be enough operators to operate and troubleshoot those systems. The theoretical knowledge is not enough to deal with these complex systems. To get the hand on experience and practical knowledge, simulators play a great role in nuclear power plants construction and operation [34].

Operator training also plays a major role in the power supply industries [35]. Spanel *et.al* [36] suggested an operator training simulator for power supply industry because of the increasing higher load of power units, increasing competition in this field and need for customer service. He described how non-technical aspects also play major role in the success and smooth functioning of these industries.

2.3.3 SIMULATOR TRAINING IN MEDICAL APPLICATIONS

In the medical field OTS has also gained a lot of popularity and is used for various applications. They are used to give hands on experience to surgeons to perform critical surgeries as shown in Figure 2-11. Laparoscopic surgeries are modern surgical techniques in which the small instruments are introduced inside the body of patients with the help of hollow tubes [37] and operations are performed without making big incisions in the body. Over 2 million Laparoscopic surgeries are performed annually all around the globe [38]. For these critical surgeries, there is always a need of skillful surgeons. For structured training, the demand of surgical training simulators has dramatically increased [39].

The innovative and more flexible training simulators also provide the advantage of tailored curriculum training for specific student audience. To include the simulators in the graduate studies curriculum has been found to be more effective than the non-dependant separate training simulators in surgical field [40]. Due to the advancement of the surgical procedures, the demand of the skilled surgeons is also increasing to perform those operations [41]. It is recommended that for effective training and teaching, the training devices included should range from high fidelity to low fidelity, i.e. the similarity to the actual clinical setup should range from less similar to exact similar. It is recommended that novice operators be trained on low fidelity with one task at a time simulator, whereas for trained operators, high fidelity simulator should be used to improvise their performance [42].

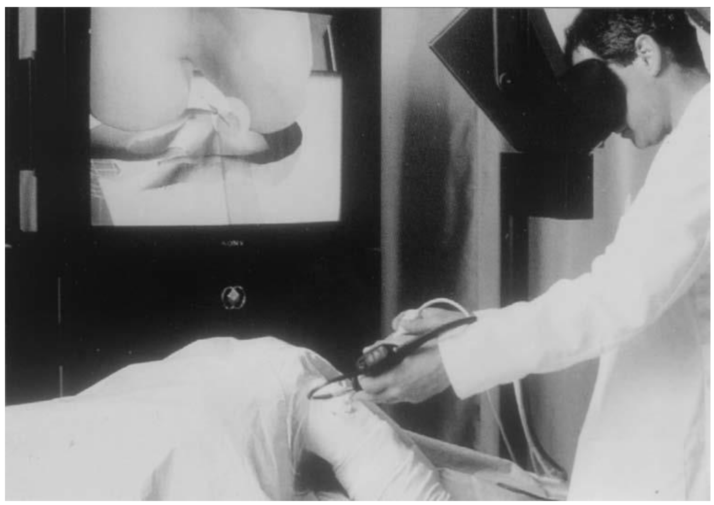

Figure 2-11 Knee simulator with mannekin knee and virtual reality image of anatomy on the monitor [40]

Laparoscopy has provided surgeons with a useful technique which benefits the patients, but it also provides a new set of skills which are to be mastered by the surgeons and for that proper training is required [43]. Improper training can lead to bad results for patients and it will also hinder the surgeons to implement the advance laparoscopy techniques. Intracorporeal surgery and knot tying is considered to be one of the most difficult skills to master in advanced laparoscopy techniques [44]. Rosser *et.al* [45] demonstrated that how Intracorporeal skills can be mastered with 2-5 day courses. It will take the novice skill workers to the same skill level of skilled workers with proper training on simulators.

In 2010, Sroka *et.al* [46] tested the effect of Fundamental of Laparoscopic surgery training simulator on junior residents in operating rooms. He used the global rating scale (GOALS) to evaluate the performance of residents. Residents having lesser score were trained on the simulator and evaluated again. It was observed that after training there was considerable improvement in their Goal score. He concluded that training simulators improve the performance of the surgeons in Laparoscopic surgery.

For the skillful surgeons also, the training simulator plays an effective role in maintaining the proficiency [47]. Structured and proficiency based training focuses mainly on performances. This strategy helps to optimize the efficiency of training by adjusting the time and amount of training requirement for that skilled individual. The learning should be in a distributed fashion to make the training more effective [48], [49].

In 2012, Heuer *et.al* [50] reported the performance of operators not only depends on practice with the simulators, but also relies on the visual feedbacks. Due to this, the performance of operators changes when they are shifted from simulators direct view to the endoscopic view as the direct view is at the angle of 50° to the surface made of blocks in which the cuts were made. As a result, the performance of operators with direct view remains stable, but with endoscopic view it varies.

2.3.4 SIMULATOR TRAINING IN AVIATION INDUSTRY

In the aviation Industry, flight simulators play an important role in training. Flight simulators as shown in Figure 2-12, help to train pilot in radio communications, system knowledge and various navigation skills [51]. There are a number of high fidelity flight simulators available. But all of these flight training schools can't afford these expensive simulators and the main challenge in aviation industry is to design and develop a simulator which is not expensive and training schools can afford to provide the basic training [52].

Figure 2-12 Pneumatically actuated motion platform for a full flight simulator, "Project ServoFlight" at the Institute for System Dynamics, University of Stuttgart [59]

The development of flight simulators started in early 20's. Edwin Link developed the first flight simulator named 'Pilot Maker' [53]. Since then, there has been a lot of development in flight simulators and now it has become a sophisticated and specialized field. Today, flight simulators are used for the training of both military and civilian pilots. Due to advanced technology it has become easy to use flight simulators for effective training and competency evaluation of flight crew members.

Training simulators are used for novice, trained continuation and recurrent training of crew members, maintenance and supervisory staff. In-flight simulators provide all the controls and feel of a real flight with high fidelity [54]. In 2012, Georghiu [55] described various performance indicators to evaluate the efficiency of the simulator. It calculates the transfer of knowledge via simulator, by calculating the time taken to learn the same concept on the simulator vs real system. He concluded that the simulator training process is faster and more economical.

The main challenge of pilot training is to meet the demands of the advanced technology that continues to change and add complexity to the learning process [56]. In 2011 Zheng *et.al* [57] proposed a prototype of high fidelity flight simulator in which their main strategy was to make the simulator training pattern not as complicated and easy to maintain. In this the executable codes for the simulator were generated with COTS software to meet the ever changing technology of a simulated environment.

In 2008, Lei *et.al* [58] developed a pc-based flight simulator for landing gear model, using object oriented C++ code written in S function. Their main approach was to make a low cost high fidelity flight training simulator to train for the landing gear. Landing an aircraft is considered to be important for flight safety. They concluded the efficiency of their simulator by comparing the results with the flight test data.

In 2016, Pradipta *et.al* [59] developed a pneumatically actuated flight simulator, which is a low cost flight simulator having 6 degrees of freedom motion platform. In this, servo motors are used to actuate the pneumatic cylinders in platform which resembles the configuration of 3-3 Stewart platform. In this an extra pneumatic cylinder was used in the middle and a redundantly actuated motion platform was used. He was successful in making the platform follow the reference position with small deviation.

In the rescue operations, the demand of the helicopters is increasing as they are more flexible for medical emergencies and for harsh environment [60]. There are many simulators designed to train operators to tackle the emergency conditions with helicopters. In this paper, Hytten *et.al* [61] proved the effectiveness of training provided with a simulator. Four out of five people survived in a helicopter crash and those four people were trained on simulator. One crew member who died was untrained. There are several other papers in which the importance of training simulators is explained for the helicopter crew members [62], [63], [64].

Training simulators are also used for Marine navigation [65]–[67], driving schools [68]–[70] and also in the education sector [71]. They have a vast application and a number of studies are going on to make them more close to reality.

2.4 SUMMARY

In this chapter some basic knowledge of jet engines was covered. Different components of the jet engine were explained briefly and an overview of compressor maps was presented. Various types of jet engines and basic variables/parameters were also described. In the literature review, the role and use of training simulator was studied for various industries. It was observed that in almost every industry, where advanced and up-to- the- minute technology is used, the training simulators are of great advantage.

3 DEVELOPMENT OF SIMULATOR

3.1 INTRODUCTION

This chapter presents the design and development of a training simulator for aviation engine testing operators. An engine designing software GASTURB is used for developing the training simulator. The instruments which are being used for the research are mainly control panels having switch buttons, a throttle lever and monitor screens as shown in Figure 3-1.

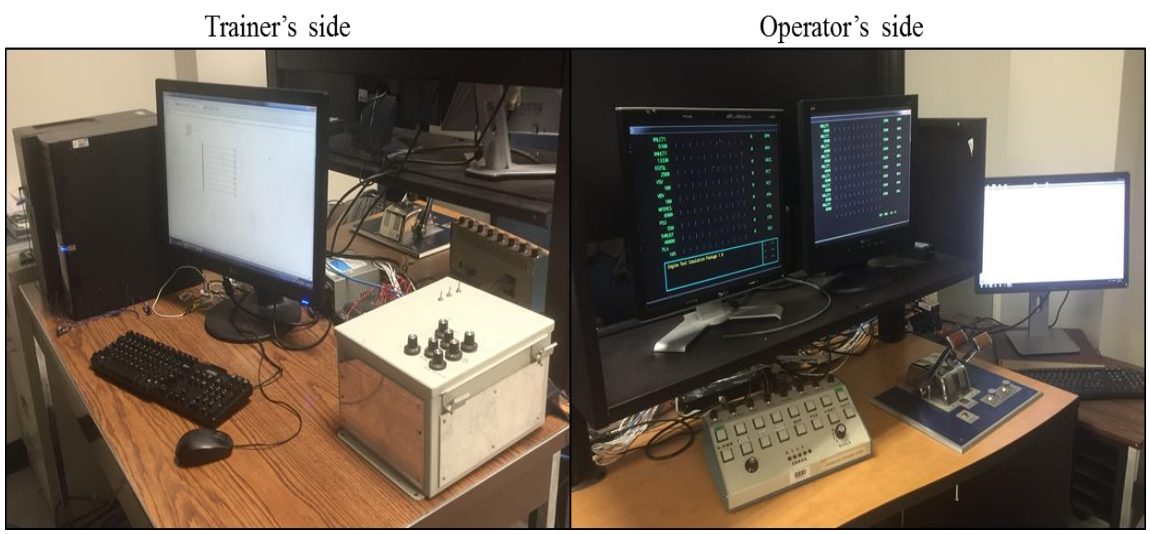

Figure 3-1 Training simulator for engine testing operators

3.2 DESCRIPTION OF SIMULATOR SETUP

The training simulator was equipped with throttle lever and control panels as input to the aviation engine model file running in Simulink. On the trainer side the Simulink model was designed to access the model file with GasTurb DLL. Various emergency scenarios have been designed to evaluate the performance and reactions of the operator. For the qualitative analysis of the simulator, a questionnaire was prepared to get the reviews from the operators and to know the effectiveness of the training simulator. On the trainer side, controls were provided to easily switch from one emergency scenario to another and also all the performance data of the operator was saved to one of the file in MATLAB which can be accessed later to evaluate the performance of the operator. On the operator side, controllers were provided to start the engine and to handle the emergency situations. The operator had to follow the instructions provided to start the engine and to use the controls in proper manner as the emergency condition may prevail. They had to perform two types of standard tests (Power calibration test and Vibration survey test) with different emergency scenarios discussed in section 3.4.2. Complete flow of information on operator and trainer side is explained by the block diagram shown in Figure 3-2.

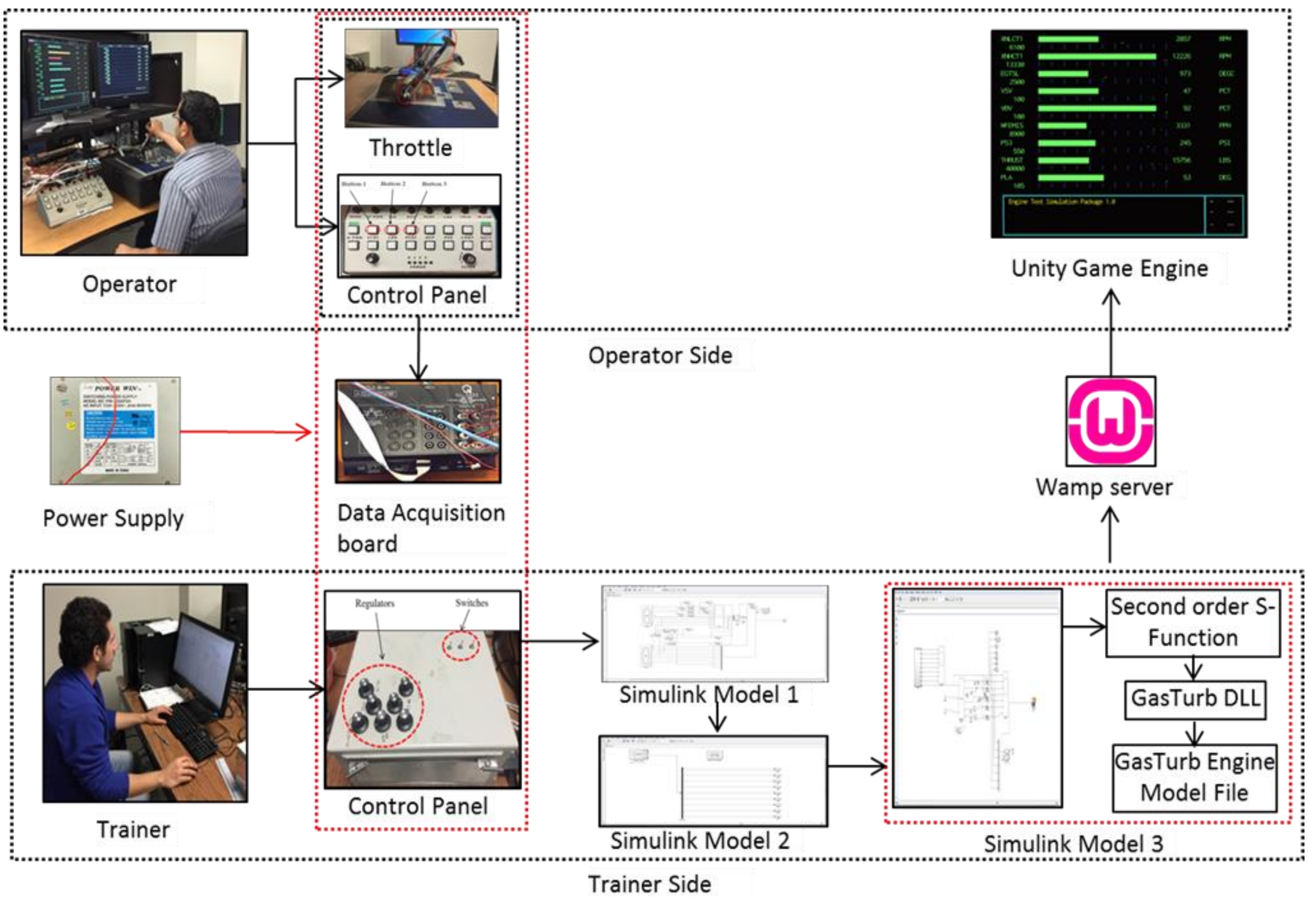

Figure 3-2 Information flow in simulator

3.2.1 HARDWARE

3.2.1.1 CONTROL LEVER

The control lever is used in the testing, research and development center (TRDC) of GE aviation by the operators for controlling the engine. It is used to start and shut off the fuel in the engine and also to control the throttle of the engine. Control lever consists of two levers; the position lever and the throttle lever. The position lever is used to control the fuel flow of the engine and to shut down the engine and has three positions.

Position 1 (Off state) – In this position there is no fuel supply and this is fuel cut-off position.

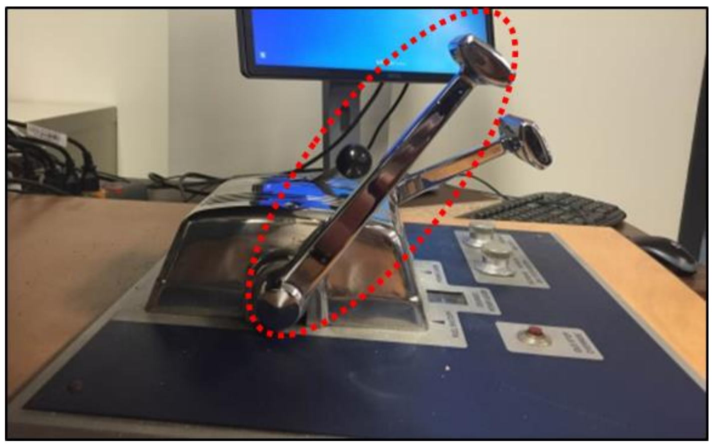

Figure 3-3 Position 1 (off state)

Position 2 (Idle state) – In this position there is fuel flow and the engine is at its idle condition.

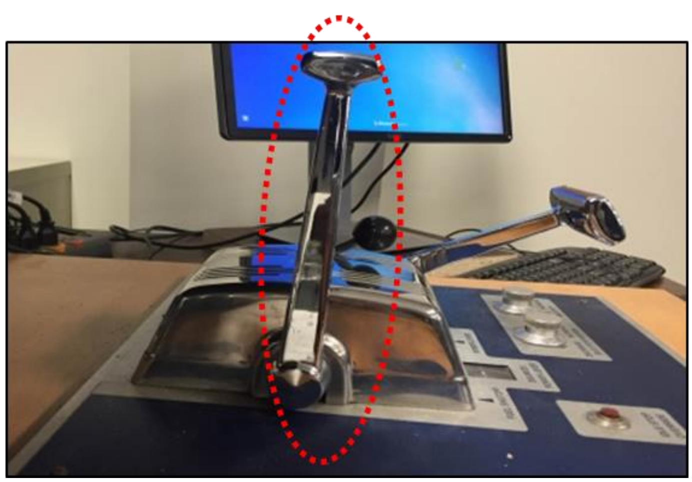

Figure 3-4 Position 2 (idle state)

Position 3 (Run state) – In this position fuel is on and throttle lever (Range from 34 to 103) is activated.

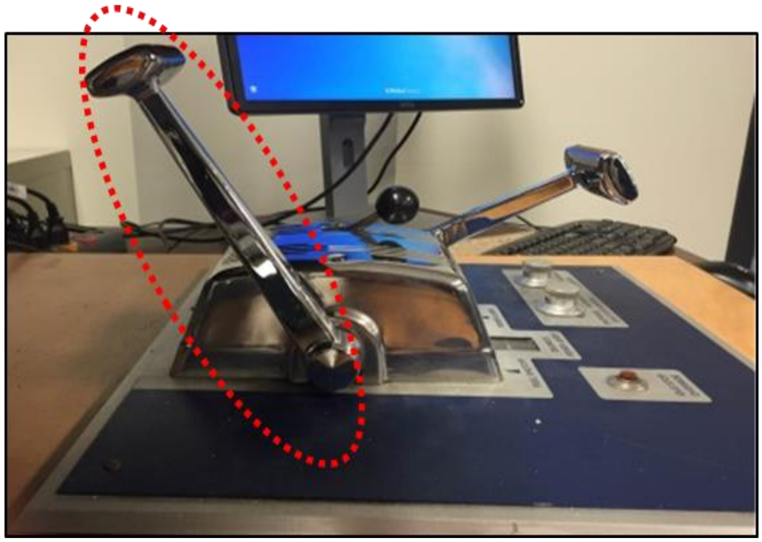

Figure 3-5 Position 3 (run state)

In position 3, the throttle lever comes into the play and the engine variables are controlled by the movement of the throttle lever.

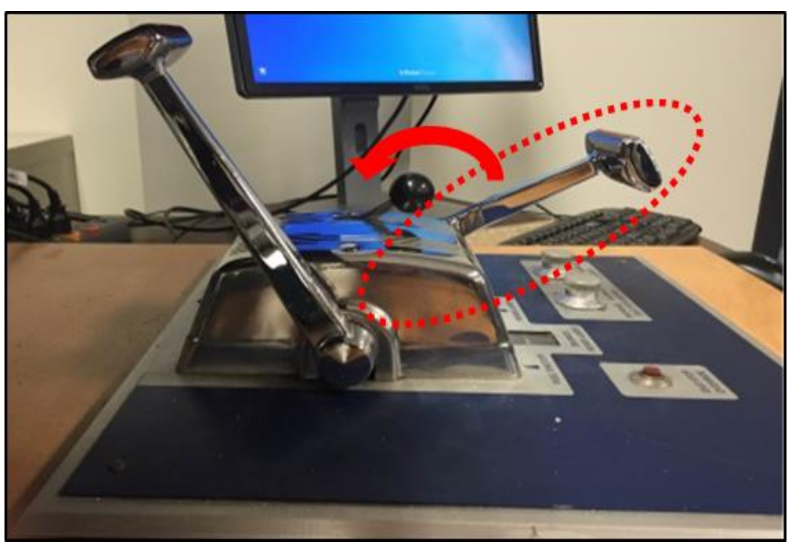

Figure 3-6 Throttle lever play

3.2.1.2 CONTROL PANEL FOR OPERATOR

This panel mainly has the controls for starting the engine and for emergency shut down of the engine as shown in Figure 3-7. The engine is either started with air pressure or motored with the compressed air and these buttons are to be pressed to start the engine.

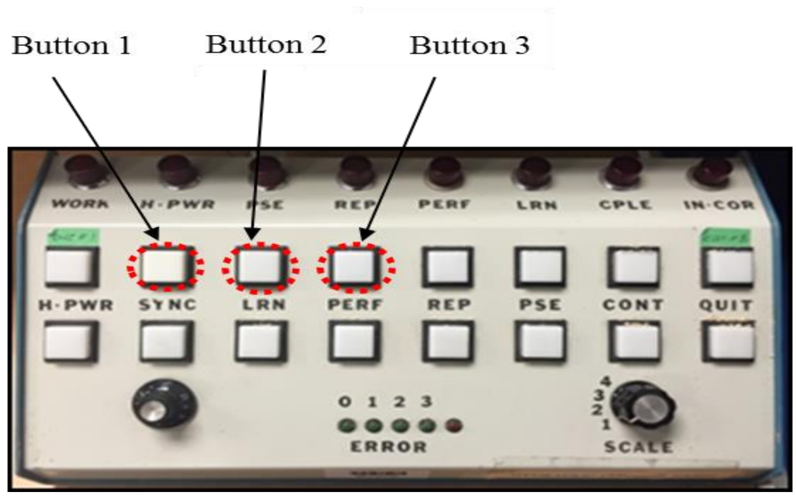

Figure 3-7 Control panel for operator

Button 1 (Air Start) – This button is used to start the engine using compressed air. Then you need to add the fuel to go to the idle position.

Button2 (Emergency Shut off) – This button is used to immediately cut the fuel off. This is used when an emergency condition emerges due to the uncontrollable variables of engine.

Button 3 (Emergency Motor) - This button is used when the intention is to motor the engine with compressed air without adding the fuel. This button is pressed to slowly cool down the engine i.e. when there is emergency shut down and engine is still hot.

3.2.1.3 DATA ACQUISITION BOARD

Quanser make 08-USB board is used for data acquisition. The Q8-USB is supported by the QUARC block set in Simulink (MATLAB). This board is having 8 digital and analog inputs and 8 digital and analog outputs as shown in Figure 3-8.

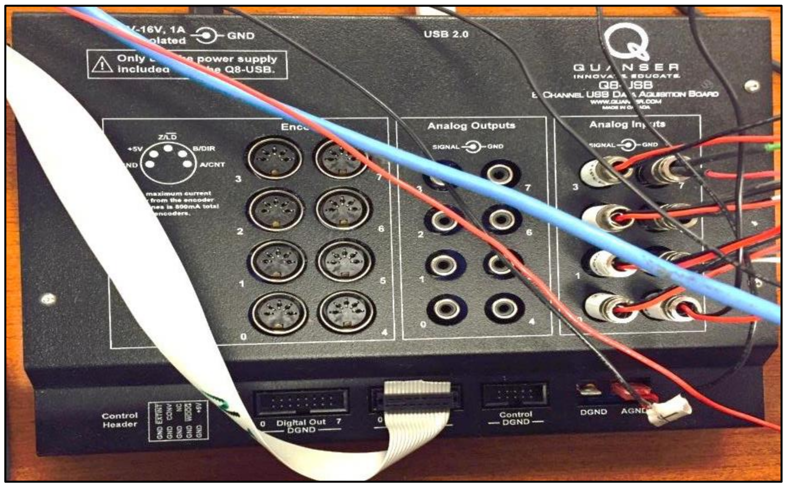

Figure 3-8 Data acquisition board

It is connected to PC with USB 2.0 port and a block set of Quanser is required in the Simulink. It is a 16-bit device with following operation voltage.

Table 3-1 Input/output operation voltages for analog/digital ports

TYPE	INPUT	OUTPUT
ANALOG	± 5V, ± 10 V	± 10.8 V, ± 10 V ± 5 V, 10.8 V 10 V, 5 V
DIGITAL	1.5 V / 3.5 V	0.55 V / 4.50 V

With this data acquisition board the throttle lever and all the control panels are connected and it further transfers those signals to Simulink (MATLAB). Those signals are changed into meaningful inputs and outputs in MATLAB. Power supply to this data acquisition board, control panels and throttle lever is provided by an external power supply.

3.2.2 SOFTWARE

The power lever throttle, two control panels and the data acquisition board gives input to the Simulink, which further use the engine model file to generate the required variables used for training purpose of operators.

Training Simulator has a power lever throttle which acts as an input to engine model file via Simulink (MATLAB) and generates various variables based on the design of the working design graph of engine model files created with engine simulation software. Simulator also uses two control panels, one on the operator side and other on the trainer side. The control panel on the trainee side is used to start the engine with compressed air, to emergency shut down the engine and also to motor start the engine, whereas the control panel on the trainer side is used to introduce various emergency scenarios and also to manually increase or decrease the variables while the simulator is in operation.

The user interface on the operator side is designed in Unity Game software, in which the data is feed by a database. That data base was created using Wamp, SQL and C# language.

3.2.2.1 GASTURB

GasTurb is a gas turbine cycle program which is very powerful and versatile. It has a user friendly graphical interface for simulating the different types of aircraft and power generation gas turbines. Nomenclature used is clear and no cryptic abbreviations are used. With GasTurb, it is easy to evaluate the thermodynamic cycles both for engine design and off-design of the most common gas turbine architectures [72]. In GasTurb even off design transient mode simulations are possible.

In GasTurb, off-design study was done. GasTurb was used to make the model file of an unmixed flow geared turbofan. This model file was used in MATLAB with the help of GasTurb DLL to get the variables out of that model file. The geometry of the engine was found by running the cycle design point in GasTurb.

For the off-design simulation, standard engine maps and standard design point settings were used for the unmixed flow geared turbofan model. Change in the variables could be checked by opening the model file in transient mode and using the throttle slider in that mode. Throttle slider or PLA directly controls the power of the engine. PLA is directly connected with the spool speed of the compressor in case of Jet Engines [73].

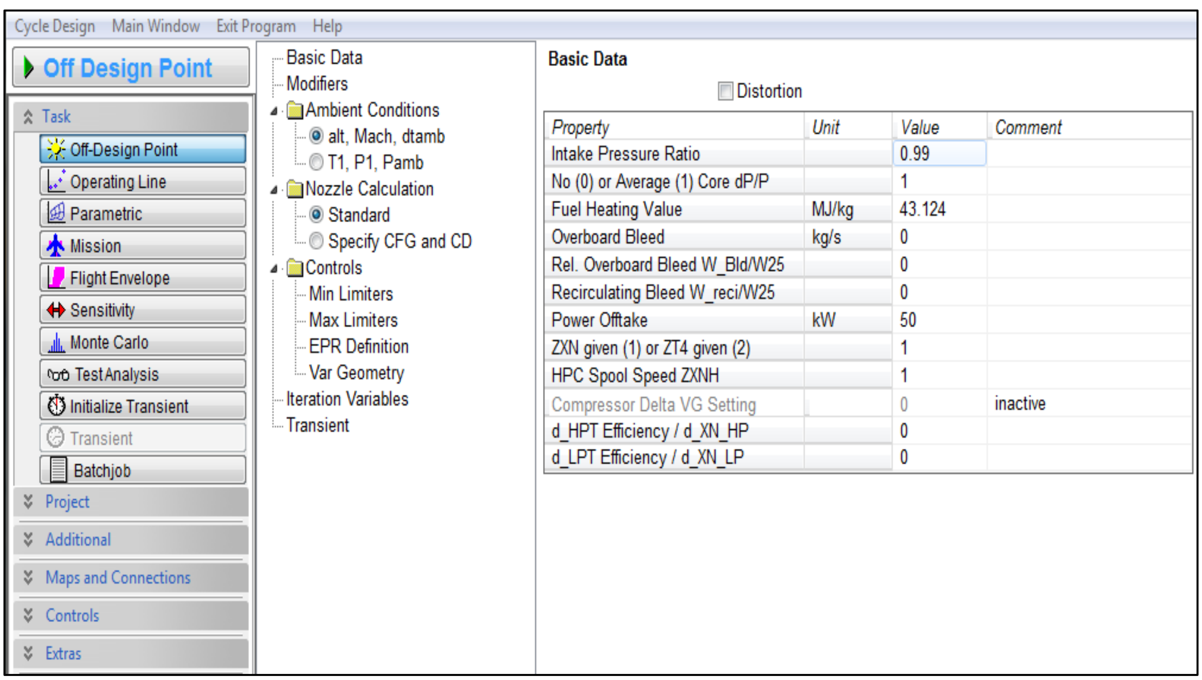

Figure 3-9 Off-design inputs

Once the model file is generated, in off design the changes can be made on the basic data such as ambient conditions, nozzle calculations and limiters as shown in Figure 3-9. After the off design inputs are decided, off-design point is calculated. Before actually starting transient simulations, calculation mode is initialized by calculating a reference operating line. This could be done by selecting the operating line tab. An operating line is a series of points with equidistant values of high pressure spool speed, thrust or power, starting with the respective value of the last calculated single off-design point [73]. The transient simulation begins with steady state operation at the operating point which has been calculated as a single cycle. Once the operating line is drawn, transient mode can be initialized and will generate the compressor operating map as shown in Figure 3-10.

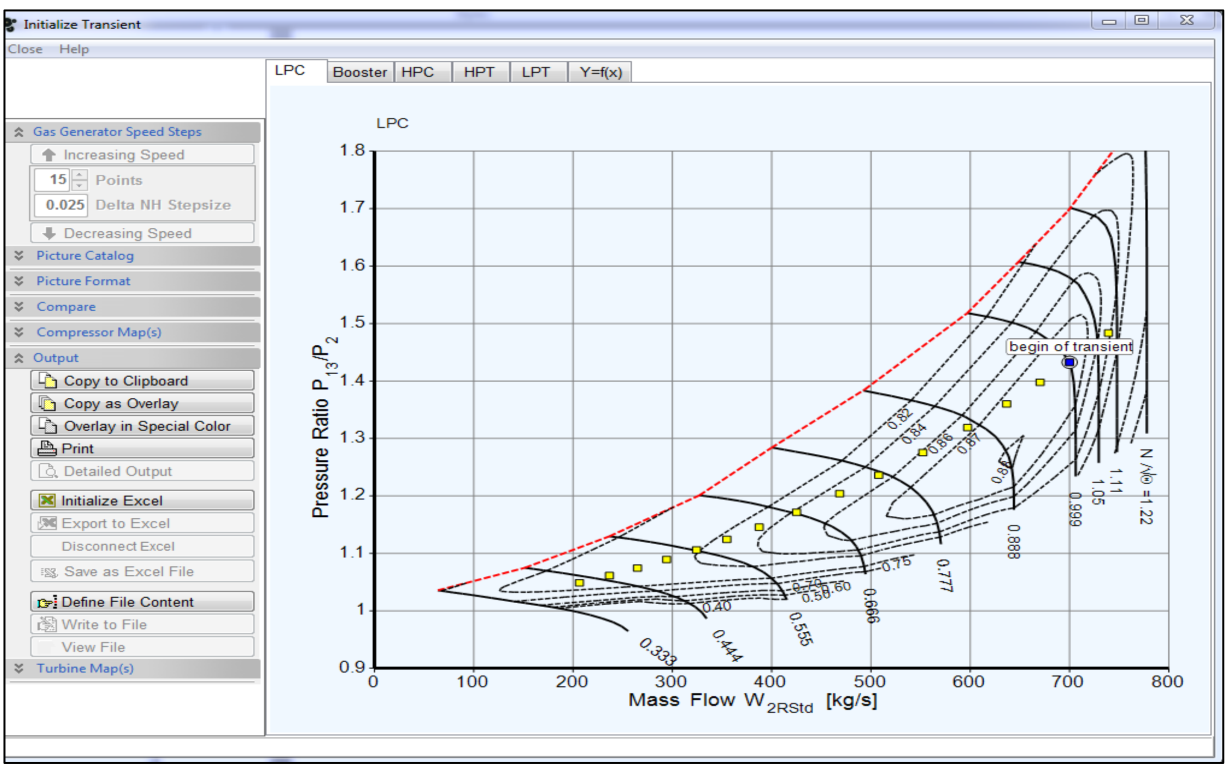

Figure 3-10 Compressor map generated by GasTurb

After initializing the transient mode, the transient tab is used to open the transient simulation window in which the effect of the change in the power lever angle can be checked on various variables as shown in Figure 3-11.

This generates the effect of PLA on the required variables and helps to simulate the model file designed. It could be compared with the desired results of engine design and modification can be done in the model file.

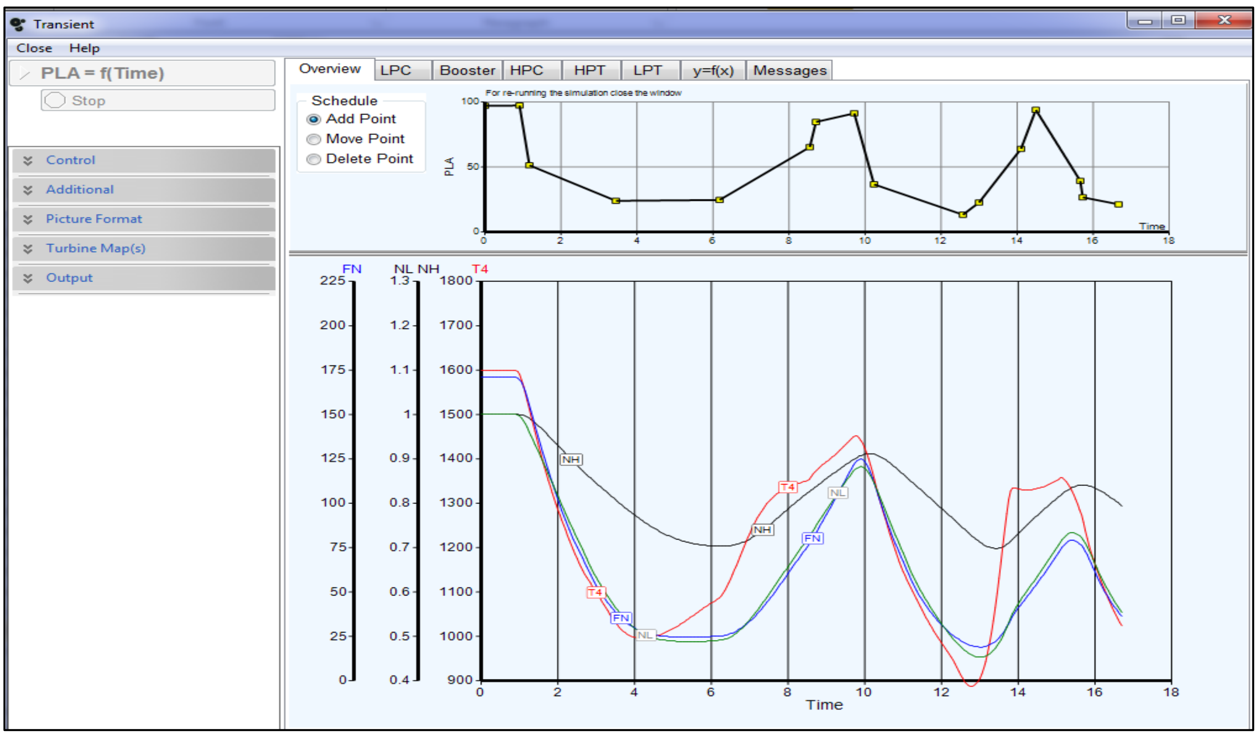

Figure 3-11 Screenshot of transient mode showing effect of PLA

3.2.2.2 NASA JAVA APPLET (ENGINESIM)

EngineSim is a free Java applet available on NASA's website for the learning purposes. EngineSim is an interactive tool that models the design and testing of turbojet engine. In this applet, both the modes are present: design mode and tunnel test mode for jet engines. There are options to switch to different jet engine models, which are pre-programmed in the applet.

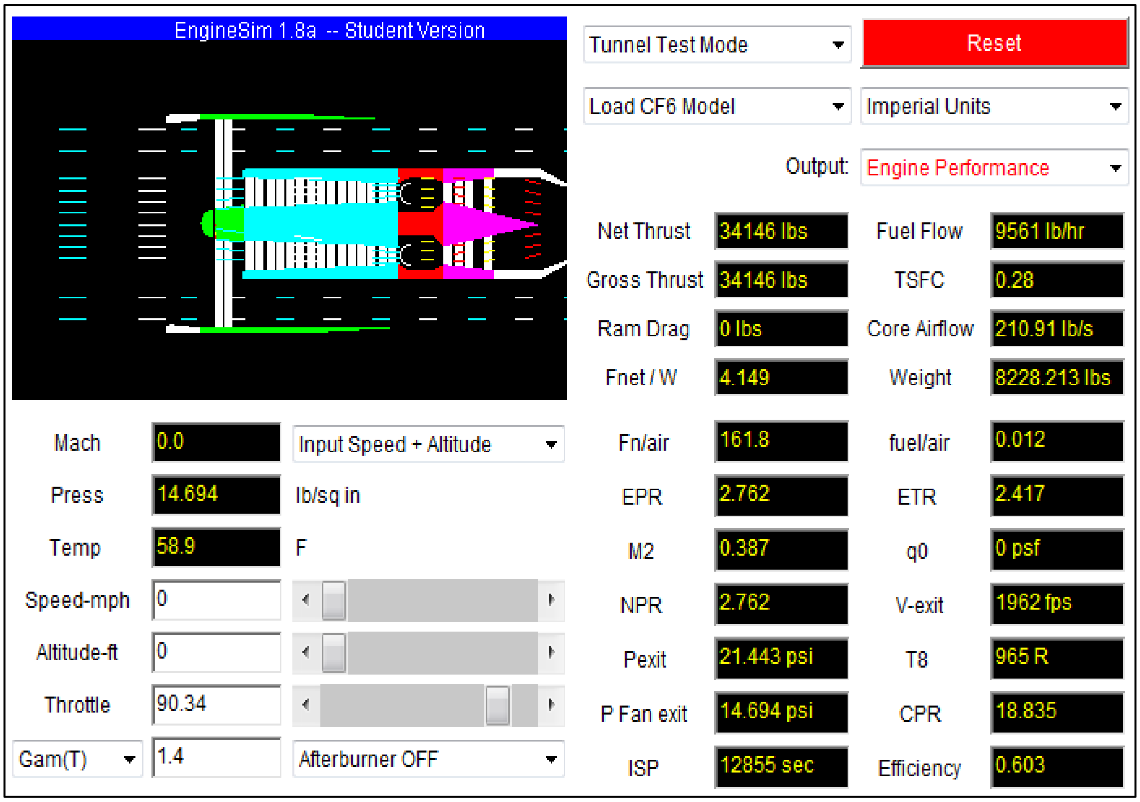

Figure 3-12 Screenshot of EngineSim

As shown in Figure 3-12 various parameters like Mach number, ambient pressure, ambient temperature and even altitude can be changed easily to see its effect on performance. There is a slider to vary the throttle to observe its effect on various variables. The NASA applet is from authenticated source and also has many features which could be useful.

The NASA Java applet could not be directly connected to the external throttle lever. To meet this purpose, the Java coding of that model was decoded. That coding was again programmed in the Simulink (MATLAB). The turbofan engine model is required for the training purpose and in EngineSim applet, CF6 is the only turbofan model as shown in Figure 3-12. It is not possible to design a new model for testing purpose and to give training on that model to the operators. The EngineSim applet is not flexible to make changes, as all the models are hard coded within.

3.2.2.3 SIMULINK (MATLAB)

Simulink is a device modelling software. This can be used to simulate numerical problems, to analyze the data, to simulate the block diagrams and to generate algorithms. The Simulink tool has been precisely designed to simulate the data flow in graphical block diagrams which is integrated with the MATLAB software. Other big advantage of Simulink is that it can be easily connected to external hardware and the data can be analyzed in real time from this hardware. In this project also, Quarc plugin is used to communicate with Quanser data acquisition board and that data acquisition board is further connected to the Throttle lever, control panels and power supply. Another advantage of Simulink is that by programming an S-function, one can easily include the DLL of other software and can use to generate results from it. Emergency scenarios can be programmed by using that data. Graphs formation and result comparison is easy.

The challenging part of this project was to transfer signals from external hardware as input to the GasTurb DLL and to use the variable values coming out of DLL for designing emergency scenarios. Three different models were made in Simulink to transfer the signals and inputs from external devices to the GasTurb DLL. This was done because the DLL can’t be accessed without creating second order S function which has to run in the model in normal mode. But the problem was that to connect the external devices and to run the Quarc plugin, the model should run in external mode. Therefore, to transfer the signal from the model running in external mode to the model running in normal mode, three different models were made.

In the first model as shown in Figure 3-13, all the signals from external hardware devices were received and were programmed to make the meaningful conditions of the system. All the system startup conditions were programmed in this bock. This model was running in external mode. All the signals were converted into one bus signal and were transferred to stream server block. Stream server block basically sends the data from the host through IP address.

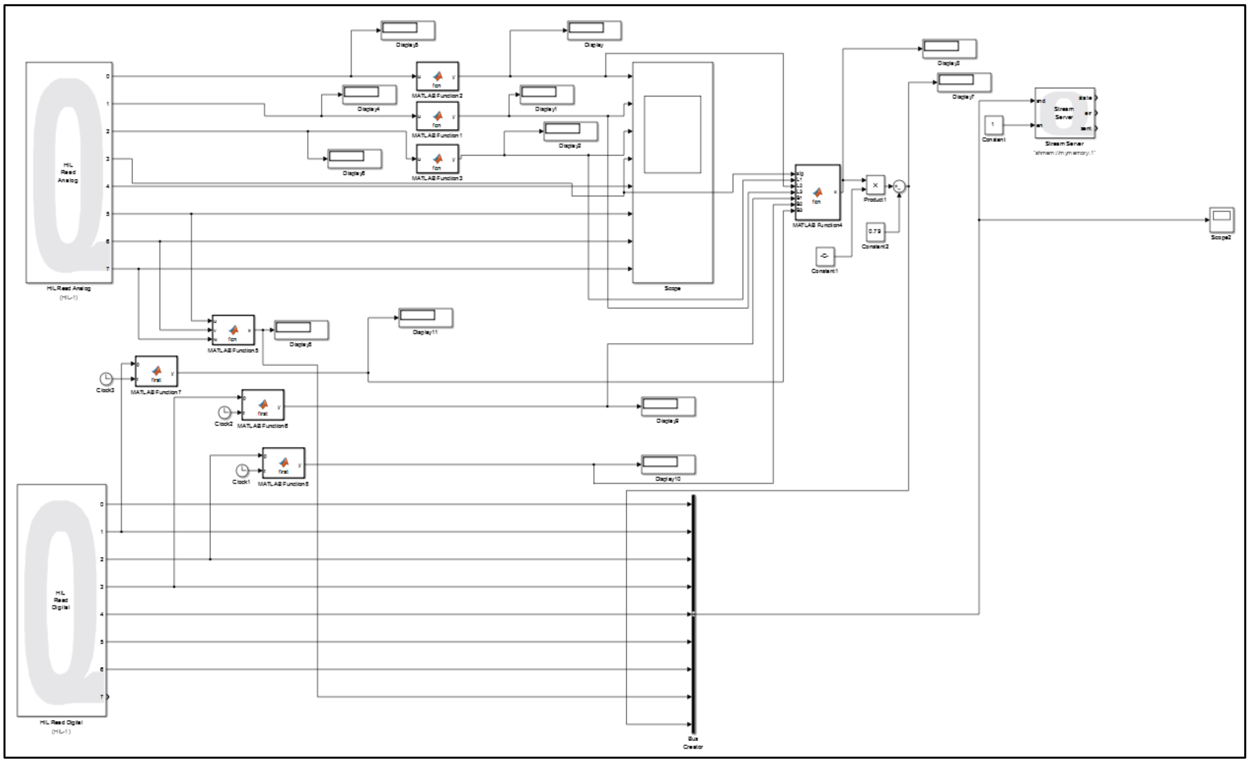

Figure 3-13 Screenshot of model 1 in Simulink (MATLAB)

The second model shown in Figure 3-14 which is basically intermediate model; a stream client block was used. This block receives the data from the first model. Second order S-function conflicts with the system time base block, so it could not be run in this model also. System time base block was used to make the stream real time at 20Hz. Consequently, this model was made as a subsystem for the third model.

Since the second model is a subsystem, the signals were sent to the out ports and in the third model it was received by using a Model reference block. This block was compatible with the second order S-function. Second order S-function is similar to the second level C-Mex function in MATLAB. In this function, complete path of DLL file and model file is provided. The number of input ports and output ports can be programmed in this function and also different variables can be decided which are required from the GasTurb DLL for the simulator.

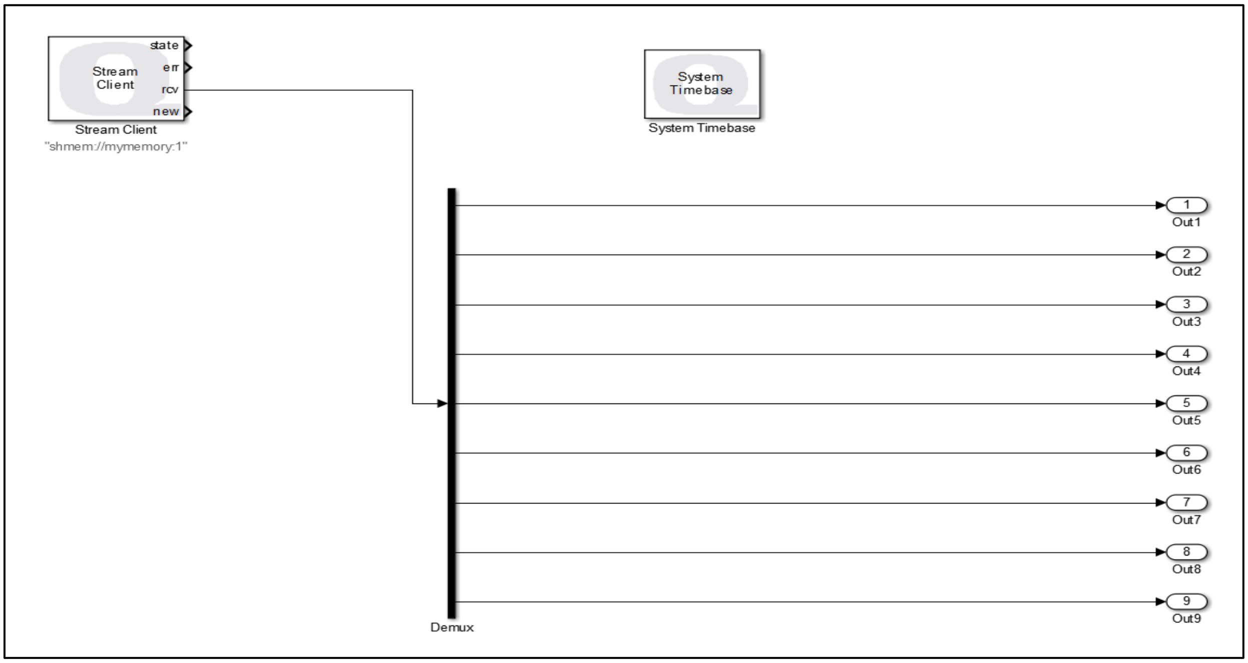

Figure 3-14 Screenshot of model 2 in Simulink (MATLAB)

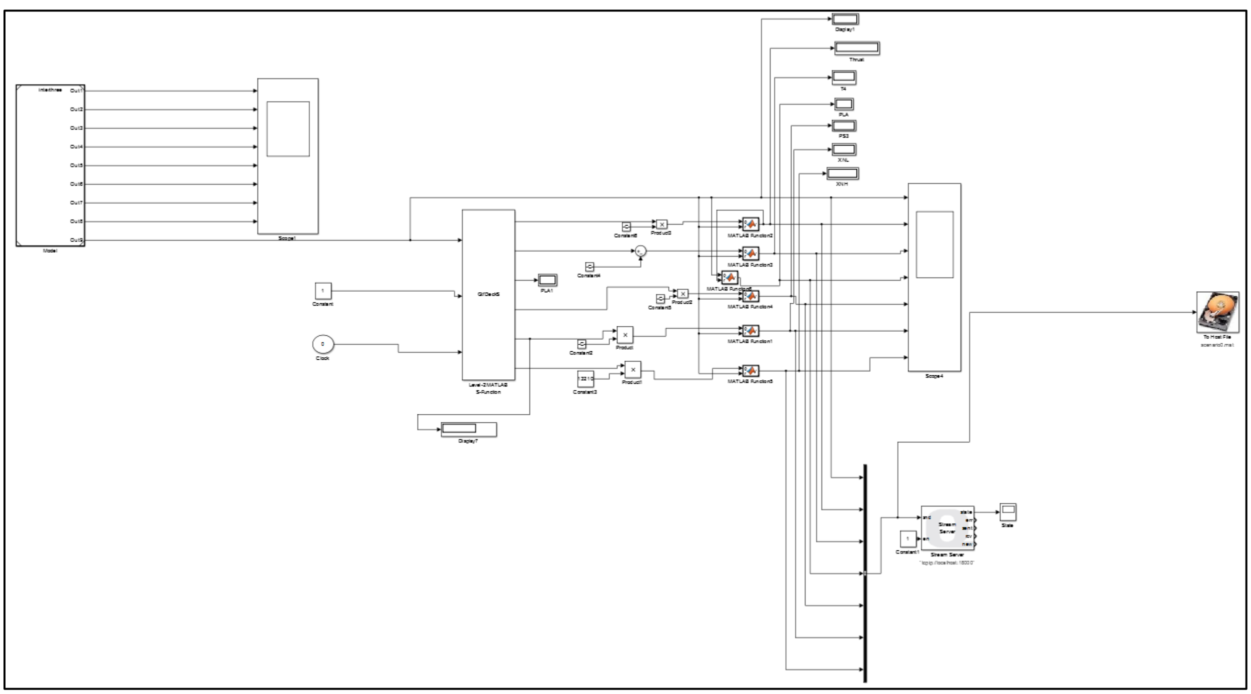

Figure 3-15 Screenshot of model 3 in Simulink (MATLAB)

From model 3 as shown in Figure 3-15 the signals are sent to the IP address of the computer on operator side with the help of 'stream server' block; a database is created in MATLAB with 'to host file' block for analysis. In the operator side computer, signals are received with WAMPSERVER where a real time database is created with MySQL. This database provides input to unity game engine in which the user interface is designed.

3.2.2.4 UNITY GAME ENGINE

Unity game engine was used to create the interface on Operator side. It resembles the interface of the systems in TRDC.

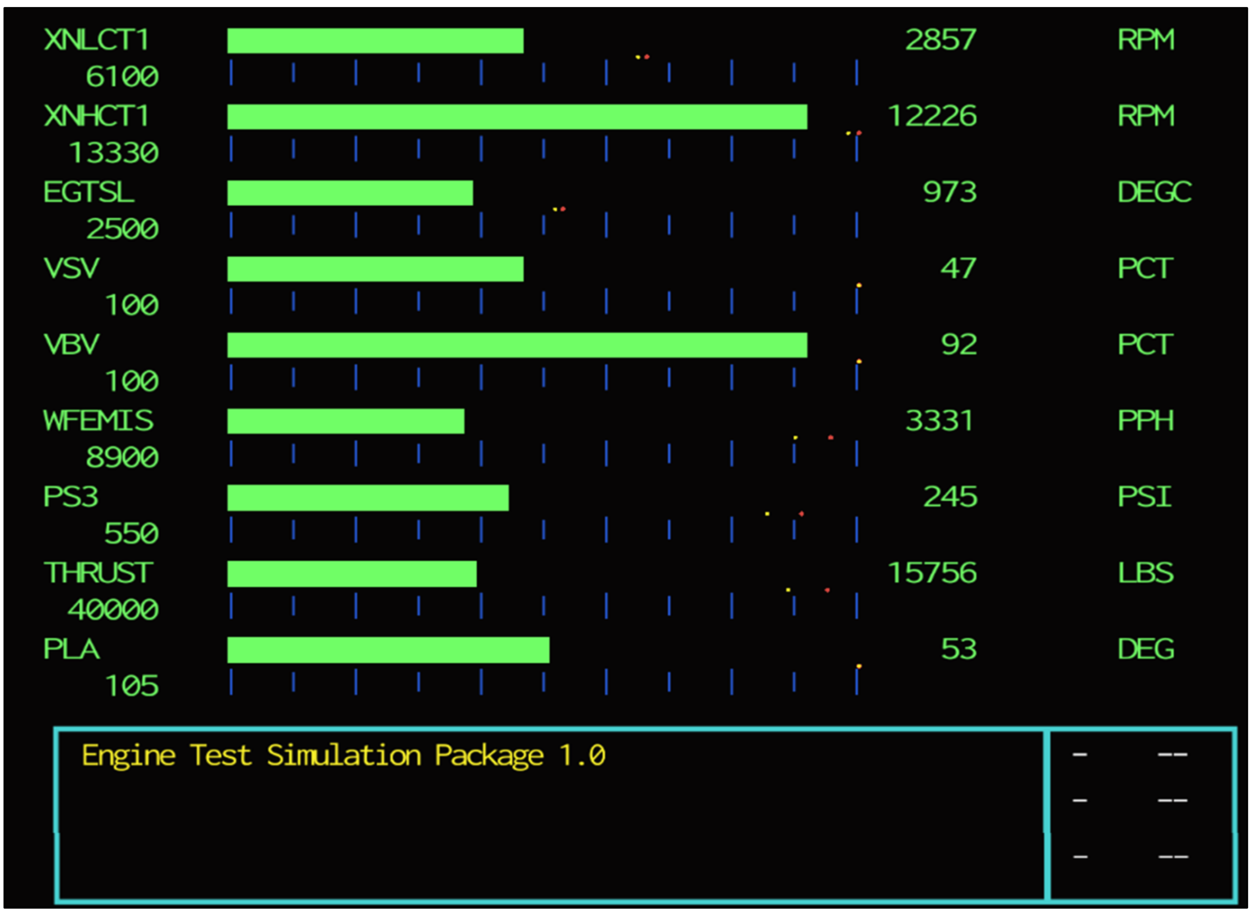

Figure 3-16 Interface designed with Unity game engine

Following are the variables on screen which get their input from the Simulink model running on the trainer side.

XNLCT1 - Fan Speed (rpm)

XNHCT1 - Core Speed (rpm)

EGTSL – Exhaust Temperature (°C)

VSV – Variable shutter valve (%)

VBV – Variable bleed valve (%)

WFEMIS – Fuel Flow (pph)

PS3 – Exit static pressure (Psi)

Thrust – Thrust of Engine (lb.)

PLA - Power lever angle (Degree)

Initially, they all have a green color which means everything is good. It turns yellow to alert the operator and to pull back the throttle. It turns red showing that immediately shut down the engine.

3.3 SELECTION OF ENGINE MODEL

As discussed in section 3.2.2.1 and section 3.2.2.2, there are two types of software available for making engine models, either GasTurb or EngineSim Java applet. As discussed, EngineSim Java applet cannot be connected directly to external throttle lever. So, the Java code of this applet was programmed in MATLAB. Also, a default model of turbofan of GasTurb was run in the Simulink. The results from both the models were studied to select the engine model file for the training simulator.

3.3.1 NASA'S MODEL RESULT

NASA model was programmed in MATLAB using various MATLAB functions. For every variables a separate function was coded. It is difficult to make changes in the coding for every engine model and also to add more variables.

Other problem with NASA model was that it was difficult to introduce more type of engines, such as turbojet or turbo prop, and to make changes in existing engine models. Hence, it was decided to look for alternative to prepare the model file for the training simulator.

3.3.2 GASTURB MODEL RESULT

The GasTurb model was prepared as discussed in section 3.2.2.1 and 3.2.2.3 and was run in the Simulink (MATLAB) for geared turbofan. It was observed that model prepared in GasTurb was giving meaningful values for different variables as shown in Figure 3-17, Figure 3-19, Figure 3-20.

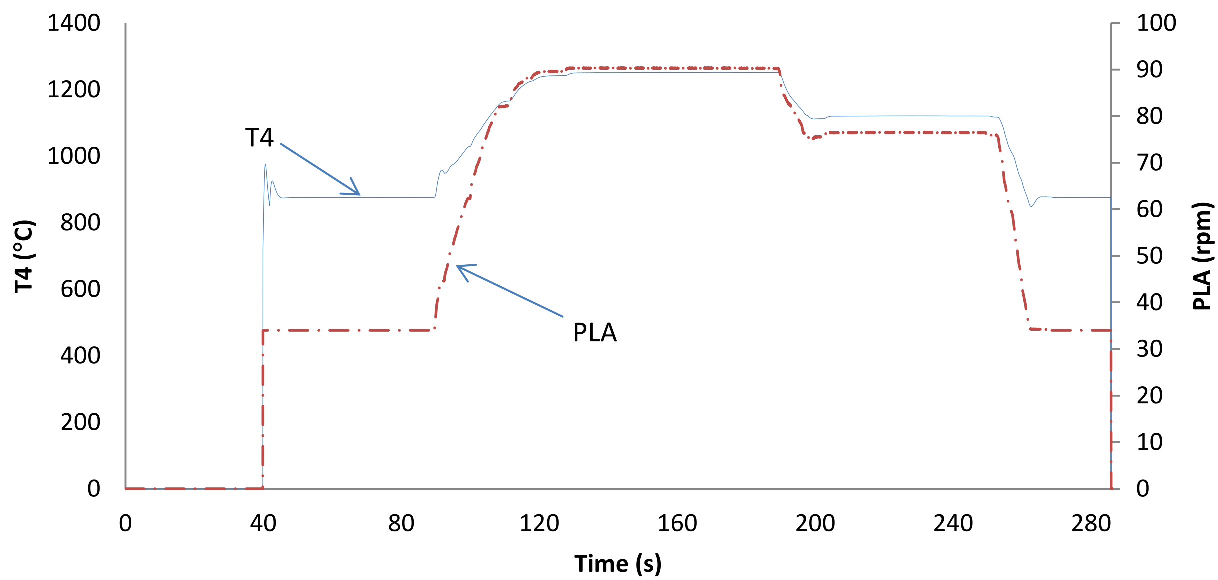

Figure 3-17 GasTurb model results for T4 vs. PLA

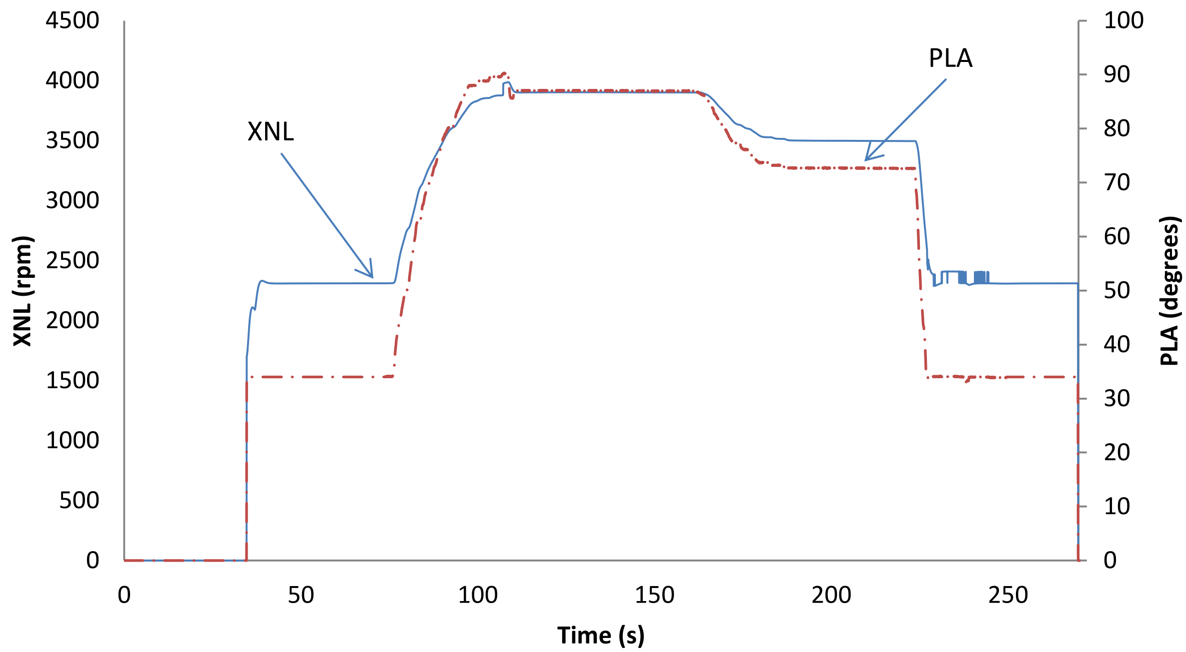

Figure 3-18 GasTurb model results for XNL vs. PLA

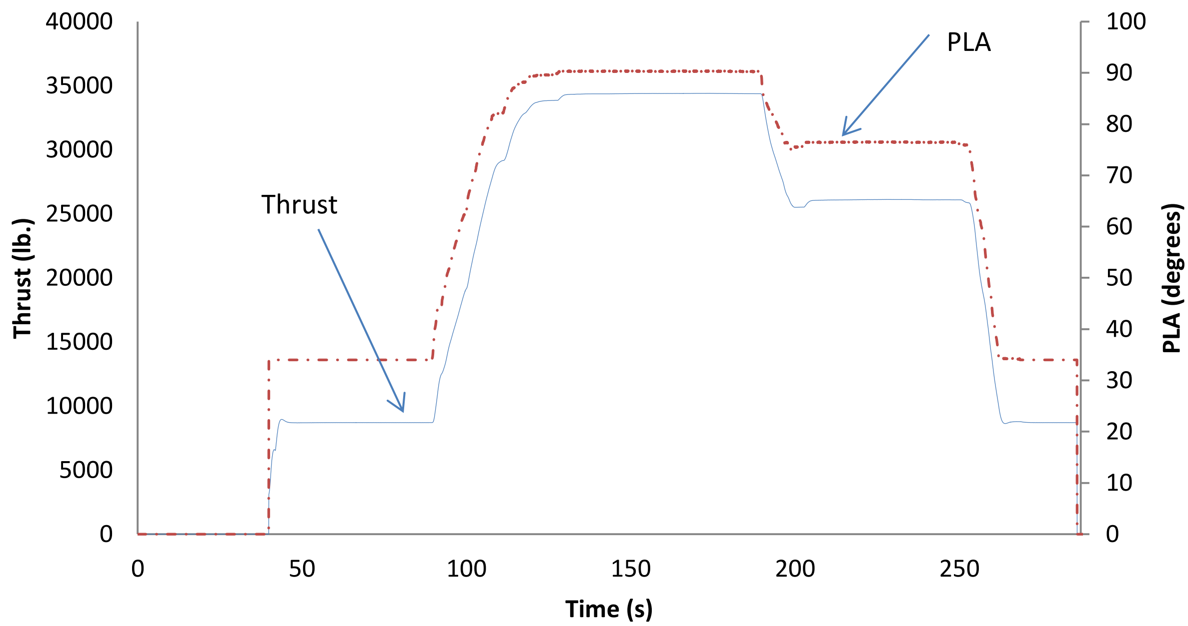

Figure 3-19 GasTurb model results for Thrust vs. PLA

It was giving results for all other variables, such as fuel flow, pressure, fan speeds and thrust. Another requirement fulfilled by GasTurb model is that it was easier to add new variables. It was more flexible and once it was embedded in the Simulink (MATLAB), it was easy to use and there was no need to program each time after making changes. It was giving more options to add different type of engines such as turboprop and turbojet. As a result, it was decided to adopt the GasTurb engine model for the training purpose.

3.4 STANDARD TESTS AND EMERGENCY SCENARIOS FOR TRAINING

The two tests were included for training purposes, which is being done on a regular basis in TRDC. Emergency scenarios were designed as per the discussions with project representatives from involved companies. It was based on the checkpoints which operators have to take care of while performing test on the engines.

3.4.1 ENGINE PERFORMANCE TESTS

3.4.1.1 POWER CALIBRATION TEST

In the power calibration test, the operator performs the following steps:

i. Slowly accelerate to ground idle (G/I).

ii. Warm up the engine at 3900 rpm.

iii. Pull the throttle lever to 3500 rpm.

iv. Again set the ground idle.

v. Proceed to shut down when approved.

Table 3-2 Test points table for power calibration test

Point	XNL [rpm]
G/I (ground idle)	Set G/I
Warm Up	3900
1	3500
2	Set G/I

Shutdown procedure for Power Calibration test is as follows:

i. Hold at G/I before shut down.

ii. Stopcock engine.

3.4.1.2 VIBRATION SURVEY TEST

In Vibration survey test, operator has to perform the following steps:

i. Proceed to vibe survey test after setting engine at G/I

ii. Slowly accelerate to 3900 ± 20 rpm XNL

iii. Hold on 3900 rpm.

iv. Slowly deaccelerate to G/I.

v. Repeat vibe survey if necessary.

vi. Proceed to shut down when approved.

Table 3-3 Test points table for vibe survey test

Point	XNL [rpm]
G/I	Set G/I
Accelerate	3900
Hold	3900
G/I	Set G/I

Shutdown procedure for Vibration test is as follows:

i. Hold at G/I before shut down.

ii. Stopcock engine.

Engine variable limits for console: The console which is designed in the Unity test engine has the limits on which it changes the color from green to yellow and red.

Table 3-4 Limits list for variables on operator side

Name	Code	E.U.	HiHi	Pri	Hi	Pri
Low spool Speed	XNLCT1	rpm	4047	2	3964	4
Exhaust Temperature	EGTSL	°C	1325	2	1295	6
High Spool Speed	XNHCT1	rpm	14000	2	13100	4
Pressure at stage 3	PS3	Psi	500	NA	470	NA
Thrust	THRUST	lb.	35500	NA	38000	NA

For every limit as shown in the Table 3-4 there is a priority assigned to it. According to that priority, operator has to react. The step which the operator has to take, according to priority, is explained in the table below.

Table 3-5 Priority numbers explanation

Priority	Step to be taken
1	STOPCOCK - Move left throttle to stopcock (fuel off).
2	RETURN TO IDLE & SHUT DOWN- Move Right Throttle, left throttle to Idle then stopcock
3	RETURN TO IDLE - Move Right Throttle, and then Left handle to Idle
4	BACK OFF- Move Right Throttle
5	MAKE ADJUSTMENT- Move Right Throttle
6	MON ITOR- N/A

While performing the engine calibration test or vibe survey test if operator sees the changes in the variables, he has to react according to the priority assigned to that change in the variable.

3.4.2 EMERGENCY SCENARIOS

Test Scenario 0 (normal) No change

Goal of scenario and expected outcome- The goal of this scenario is to emulate and study the operator's reaction when there is no change in the variables and everything is running smoothly when operator will expect some emergency situation. It is expected from the operator that he must complete the mentioned test following the complete procedure.

Trainer's side- On the trainer's side, two Simulink models will be running all the time and he has to open the third model based on the emergency scenarios he selects.

Operator's side- On the operator's side there will be Unity user interface running. And operator will have to connect to the database via Wamp server to run the Unity interface.

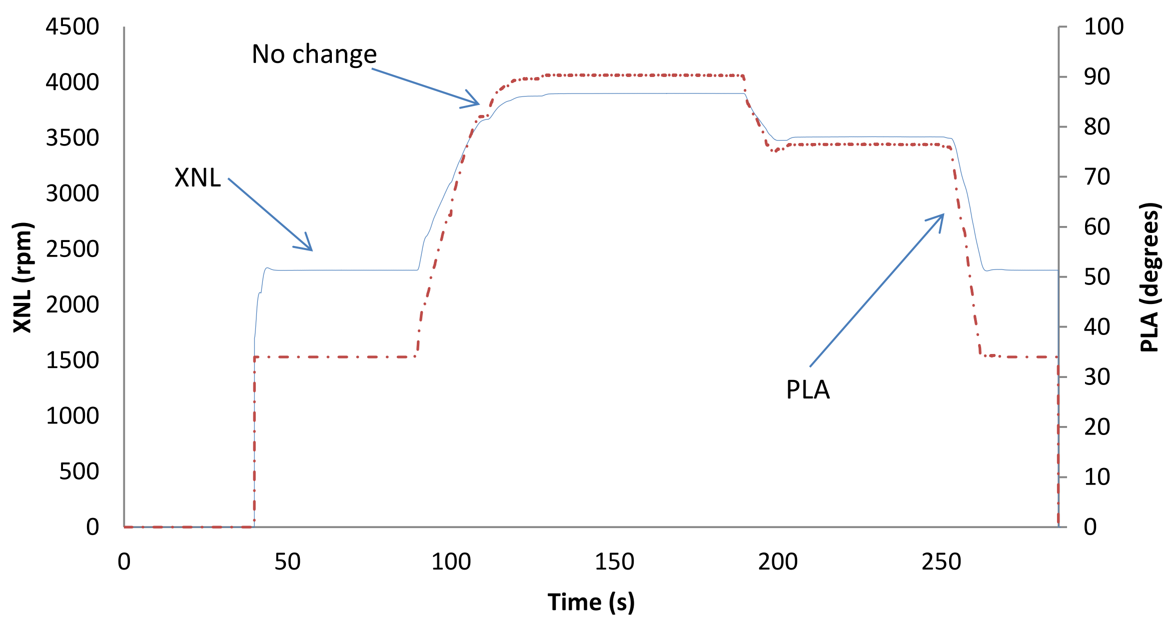

Figure 3-20 XNL vs. PLA graph for test scenario 0 (normal)

Data to be monitored- The trainer has to ensure that the operator should run the test normally. Operator should look at all other variables to ensure that they may not reach their warning limit.

Test Scenario 1- Sudden increase in Low Spool Speed after 3900 rpm

Goal of scenario and expected outcome- The goal of this scenario is to emulate and study the operator's reaction of sudden jump in the low spool speed, while the operator is trying to warm-up the engine. It is expected from the operator that he must try to bring the XNL back to the required warm-up value, by pulling the throttle lever back. He must not shut down the engine without trying to bring engine back to normal.

Data to be monitored- Trainer has to ensure that the operator should bring the throttle back to required XNL warm-up value. The operator should look at the other variables too, to ensure that they may not reach their warning limit.

Trainer's side- On the trainer's side for scenario 1, he has to open the scenario 1 file, while the rest of everything remains same.

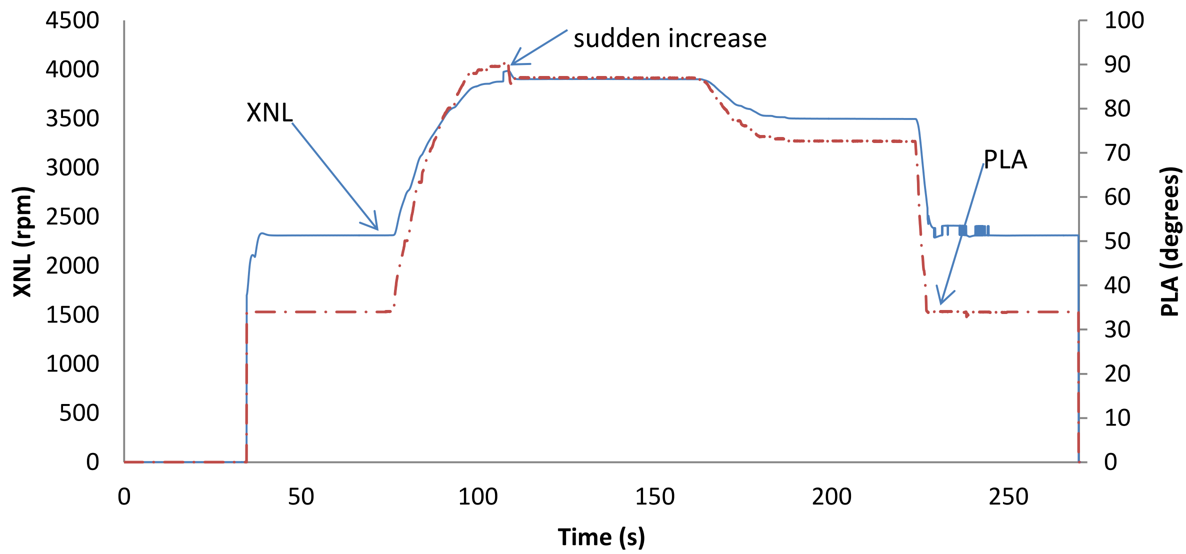

Figure 3-21 XNL vs. PLA graph for test scenario 1

Test Scenario 2- Ramp increase in XNL after 3900 rpm with no control of Throttle lever

Goal of scenario and expected outcome- The goal of this scenario is to emulate and study the operator's reaction of ramp increase in the low spool speed, while the operator is trying to warm-up the engine. After 3900 rpm there will be no control on throttle lever and speed will keep on increasing. It is expected from the operator that he must try to bring the XNL back to the required warm-up value, by pulling the throttle lever back but when he realizes that there is no control over throttle lever, he must cut down the fuel and immediately shut down the engine after that by pressing button 2 on control panel.

Data to be monitored- In this scenario, the trainer has to ensure that the operator should try to bring the throttle back to required XNL warm-up value, but after realizing that there is no control on throttle lever, he should shut down the engine completely. The operator should look at the other variables too to ensure that they may not reach their warning limit.

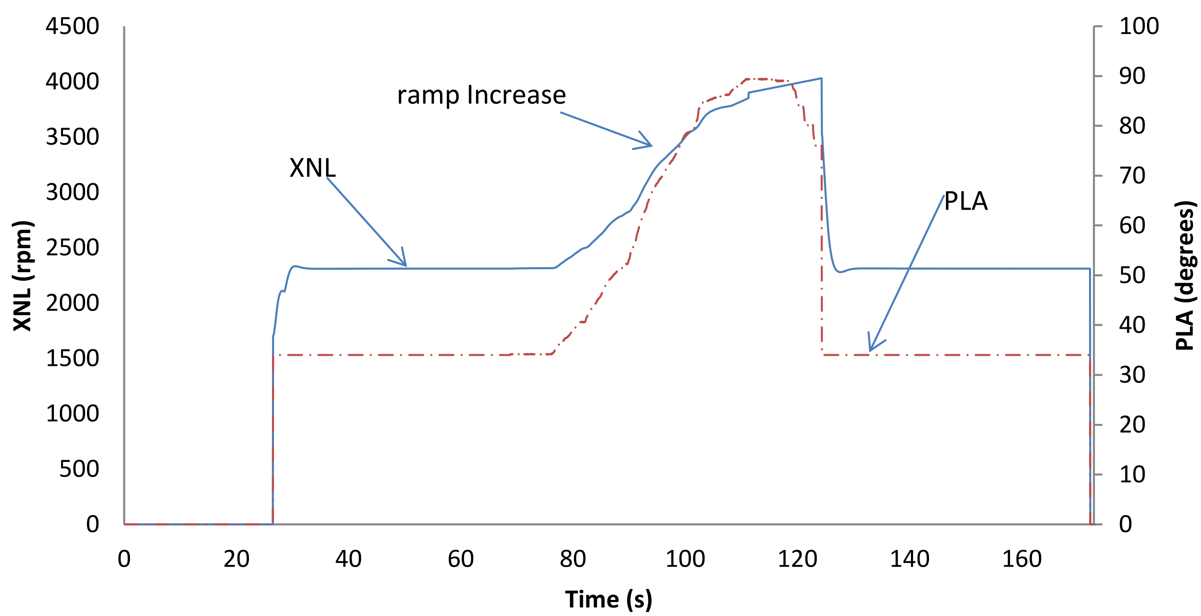

Figure 3-22 XNL vs. PLA graph for test scenario 2

Trainer's side- On the trainer's side for scenario 2, he has to open the scenario 2 file, while the rest of everything remains the same.

Operator's side- Operator has to perform the same procedure as in Scenario 0 (normal).

Test Scenario 3- Sudden increase in EGT after 1290 °C

Goal of scenario and expected outcome- The goal of this scenario is to emulate and study the operator's reaction of sudden jump in the exhaust temperature while operator is trying to warm-up the engine i.e. XNL 3900 rpm. It is expected from the operator that he must try to bring the EGT back to the safe value by pulling the throttle lever back. He must not shut down the engine without trying to bring engine back to normal.

Data to be monitored- In this scenario, the trainer has to ensure that the operator should bring the throttle back to safe EGT value i.e. operator should look at the other variables too, to ensure that they may not reach their warning limit. Therefore, while trying to warm up the engine the operator should also take care of other variables.

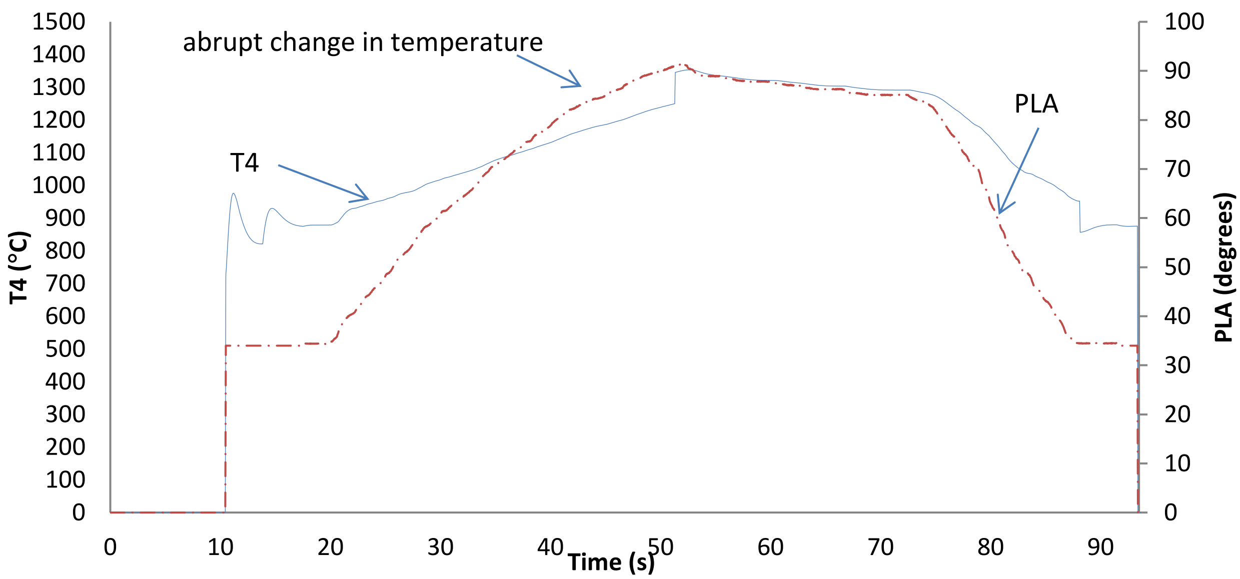

Figure 3-23 T4 vs. PLA for emergency scenario 3

Trainer's side- On the trainer's side for scenario 3, he has to open the scenario 3 file, while the rest of everything remains the same.

Operator's side- Operator has to perform the same procedure as in Scenario 0 (normal).

Test Scenario 4- Ramp increase in EGT after 1290 °C with no control of Throttle lever

Goal of scenario & expected outcome- The goal of this scenario is to emulate and study the operator's reaction of ramp increase in the exhaust temperature, while the operator is trying to warm-up the engine i.e. XNL 3900 rpm. After EGT will reach 1290 °C there will be no control on throttle lever and EGT will keep on increasing. It is expected from the operator that he must try to bring the EGT back to the safe value by pulling the throttle lever back, but when he realizes that there is no control over the throttle lever, he must shut down the engine either by cutting down the fuel or by using button 2 on control panel.

Data to be monitored- In this scenario, trainer has to ensure that the operator should try to bring the throttle back to safe EGT value, but after realizing that there is no control on the throttle lever, he should completely shut down the engine. The operator should look at the other variables too, to ensure that they may not reach their warning limit.

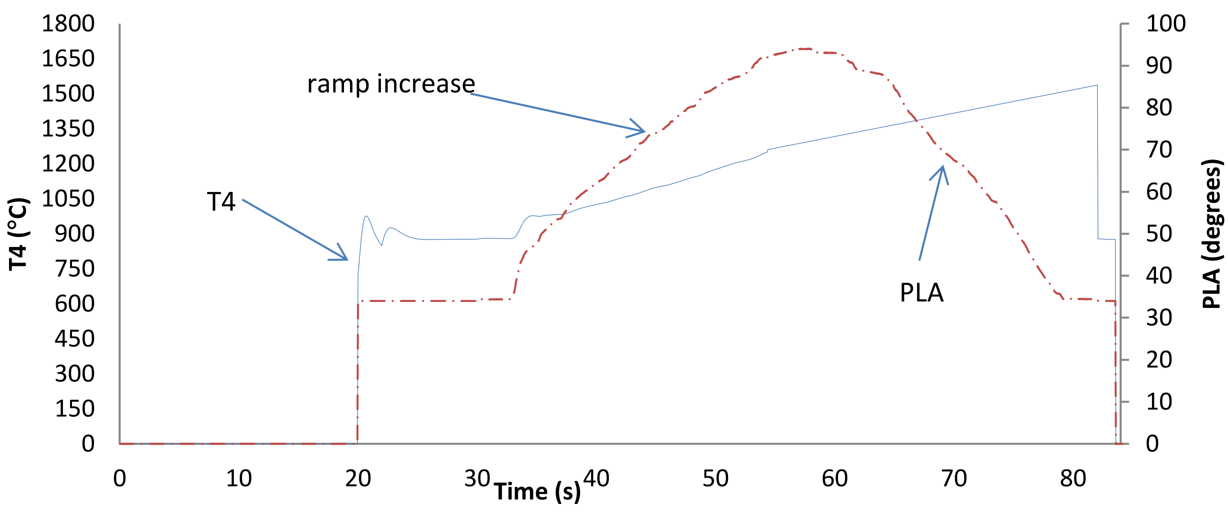

Figure 3-24 T4 vs. PLA for emergency scenario 4

Trainer's side- On trainer's side for scenario 4, he has to open the scenario 4 file, while the rest of everything remains the same.

Operator's side- Operator has to perform the same procedure as in Scenario 0 (normal).

3.5 SUMMARY

In this chapter, the simulator and its components were described. The flow of information in simulator was described pictorially. The hardware and software used while developing the simulator was discussed. Available software for engine model design (NASA and GasTurb) was tested and GasTurb was selected, as it was giving meaningful results and was found to be more flexible. The standard tests which were used for designing the training module were explained and the design of various emergency scenarios for training purpose was discussed.

4 EVALUATION RESULTS

4.1 INTRODUCTION

This chapter evaluates the capability of training simulator and include the results showing the reaction of the operators to emergency situations. The ease of comparing the performance of operators using training simulator has been discussed. The training simulator was developed to make the training process smooth and flexible without compromising the quality of training. For this purpose, a questionnaire as shown in Appendix A1 was prepared for operators to evaluate the performance of the training simulator. The result of that questionnaire and operator's feedback is discussed in this chapter.

4.1.1 PROCEDURE

The simulator which was being designed for the engine testing cell training was used by the involved participants. The participants performed tests individually in order to find out the effectiveness of the simulator. Each participant was asked to fill out the questionnaire given in (Appendix A1) after the system was tested by the participant.

The participating operators used the throttle lever and various control buttons to perform these tests. The entire test was not more than one hour. The participant had to run the simulator for about 45 minutes & the questionnaire took an extra 15 minutes of the participant time.

There were 8 participants planned for this Research project. Description of the participants is as follow:

1) Two Project coordinators
2) Two trainers.
3) Two trained operators.
4) Two Novice operators.

In the recruitment process, University of Manitoba researchers were introduced to the participants by the involved companies. It was absolutely volunteer participation. The names of the participants were withheld and they were identified only by operator # 1- Operator# 6.

4.2 TEST RESULTS

A total of six tests were designed to collect data in order to evaluate the performance of simulator. Only two trained operators were able to participate for this project due to limitation of testing operators in Winnipeg.

4.2.1 TRAINING DESIGN

As discussed in section 3.4, there were 2 tests and 6 emergency scenarios included to design the training plan. These 2 tests and 6 emergency scenarios were combined randomly as explained in Figure 4-1 to finally plan 6 test designs for the training. Each operator took these 6 tests and data was gathered to study their reactions. In this section, their reaction to emergency situations has been plotted on graph and discussed below.

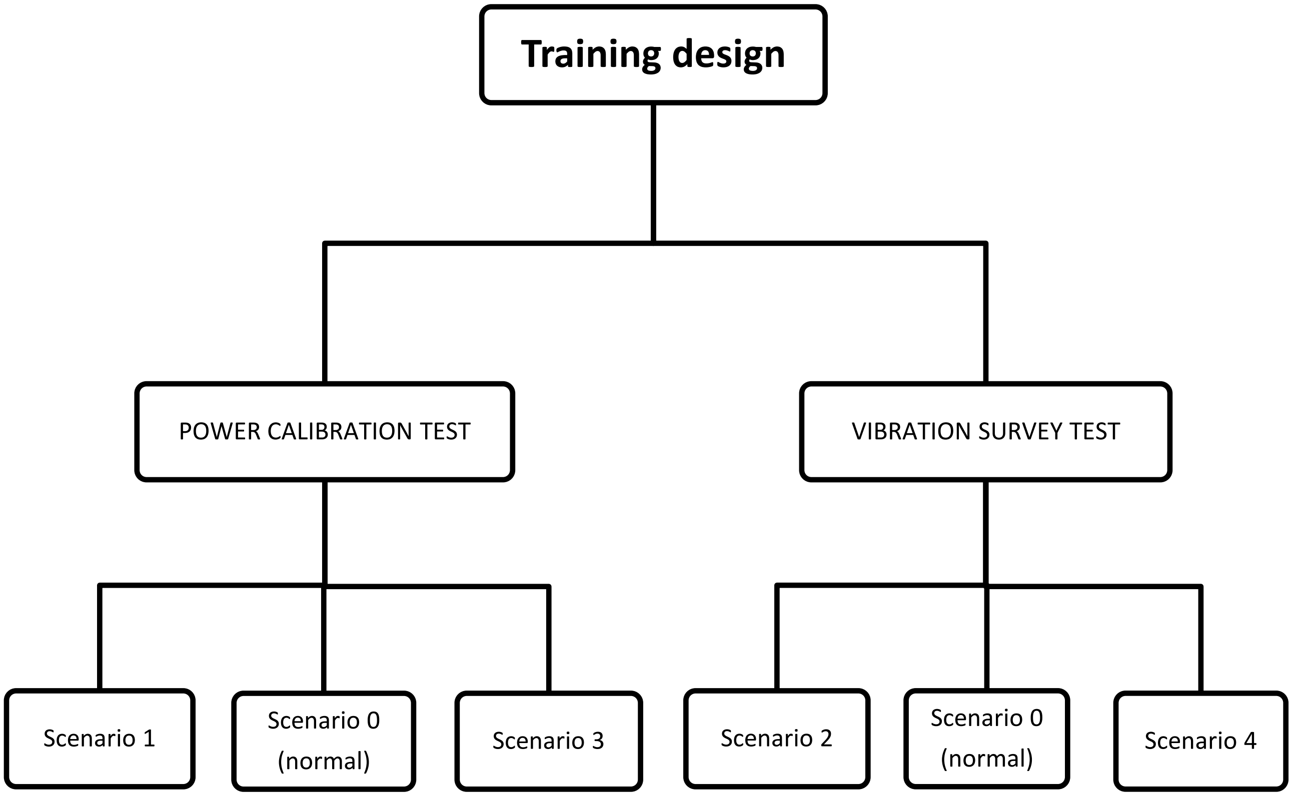

Figure 4-1 Training design

4.2.2 POWER CALIBRATION TEST WITH EMERGENCY SCENARIO 1

In the first test, the operators had to perform the power calibration test. The emergency scenario 1 was introduced while the operators were performing the test. In the scenario 1, the major variable of concern was XNL (low spool speed). The graphs of XNL v/s PLA were plotted for both the operators as shown in Figure 4-2 and Figure 4-3. While performing these tests the dwell times of the tests were not followed.

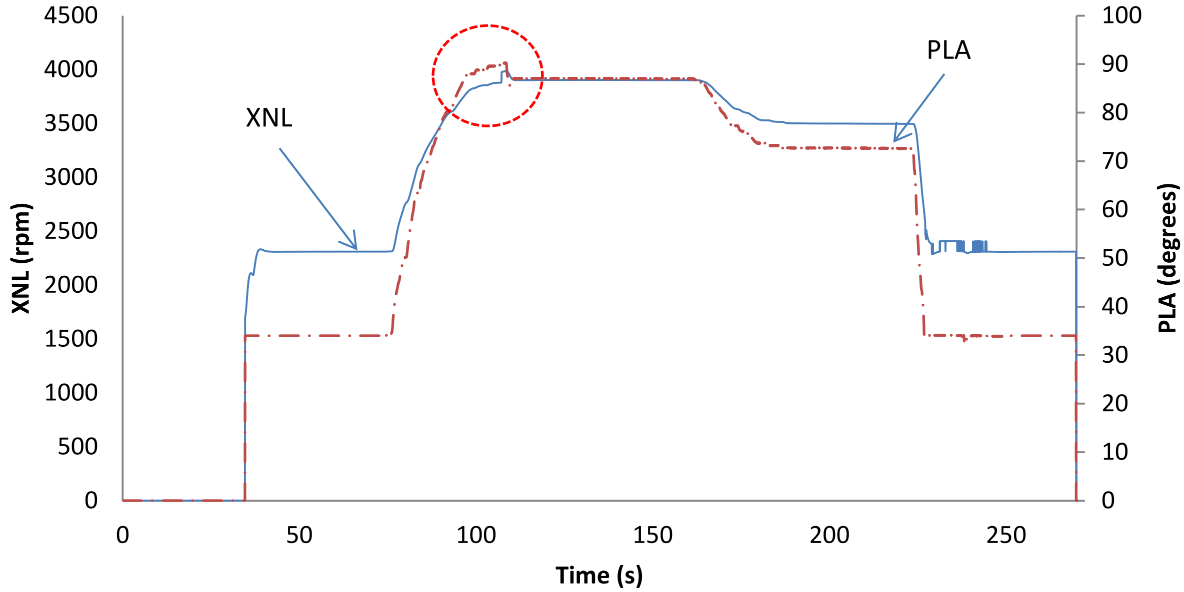

Figure 4-2 XNL vs. PLA test 1 graph for operator 1

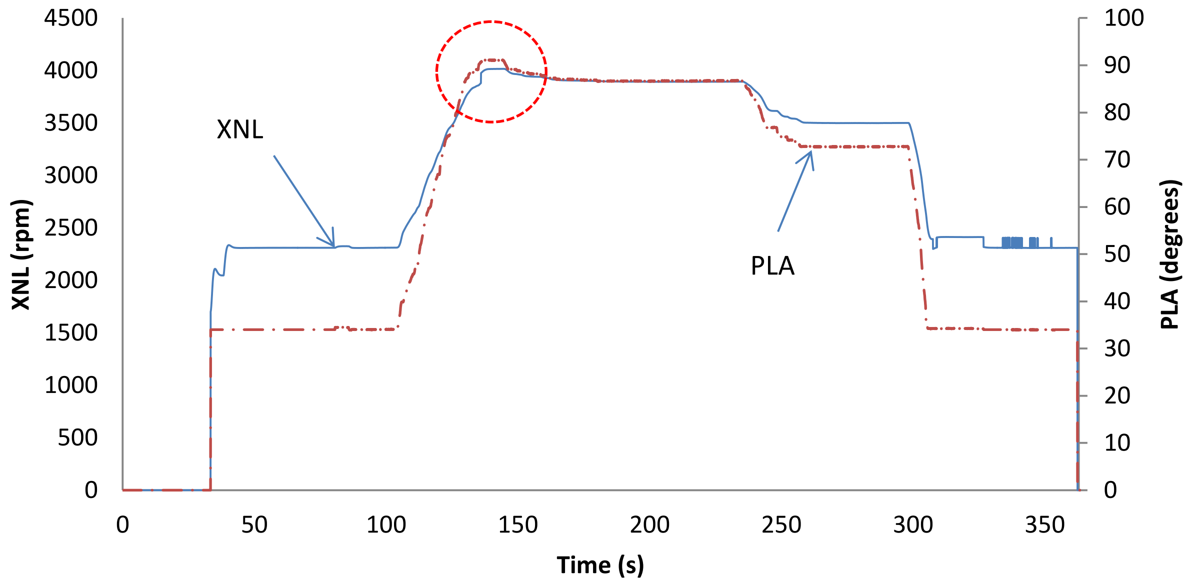

Figure 4-3 XNL vs. PLA test 1 graph for operator 2

For close analysis of the operator's reaction to this emergency scenario, the graph was zoomed to the highlighted area to check the time taken by each operator to control the situation.

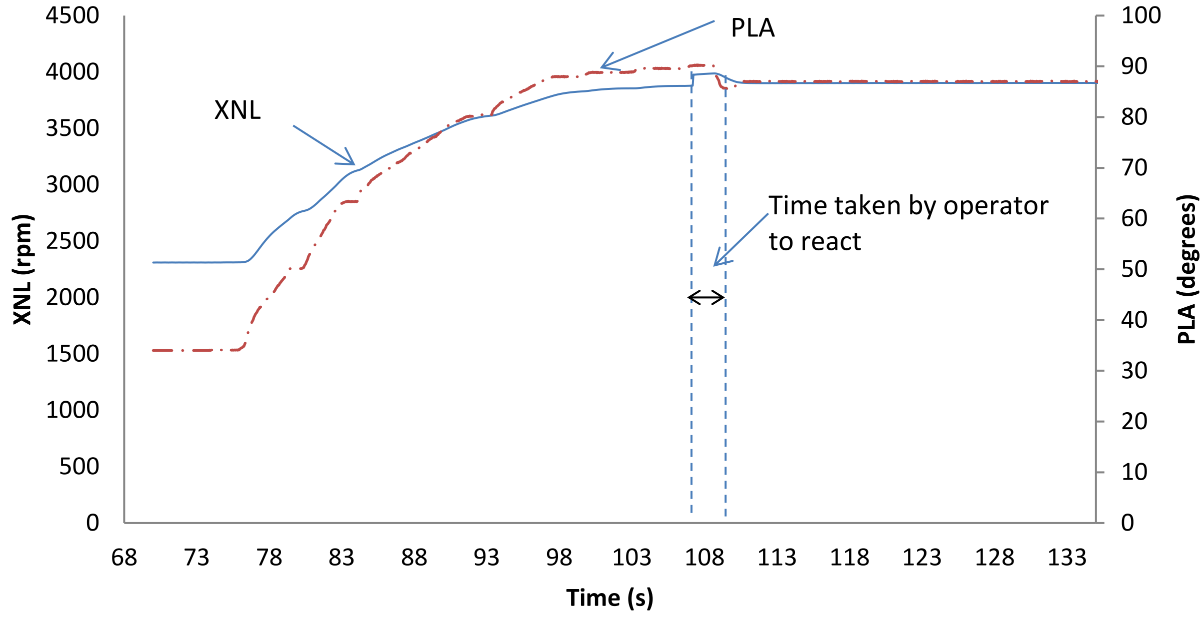

Figure 4-4 Zoom in graph of XNL vs. PLA test 1 for operator 1

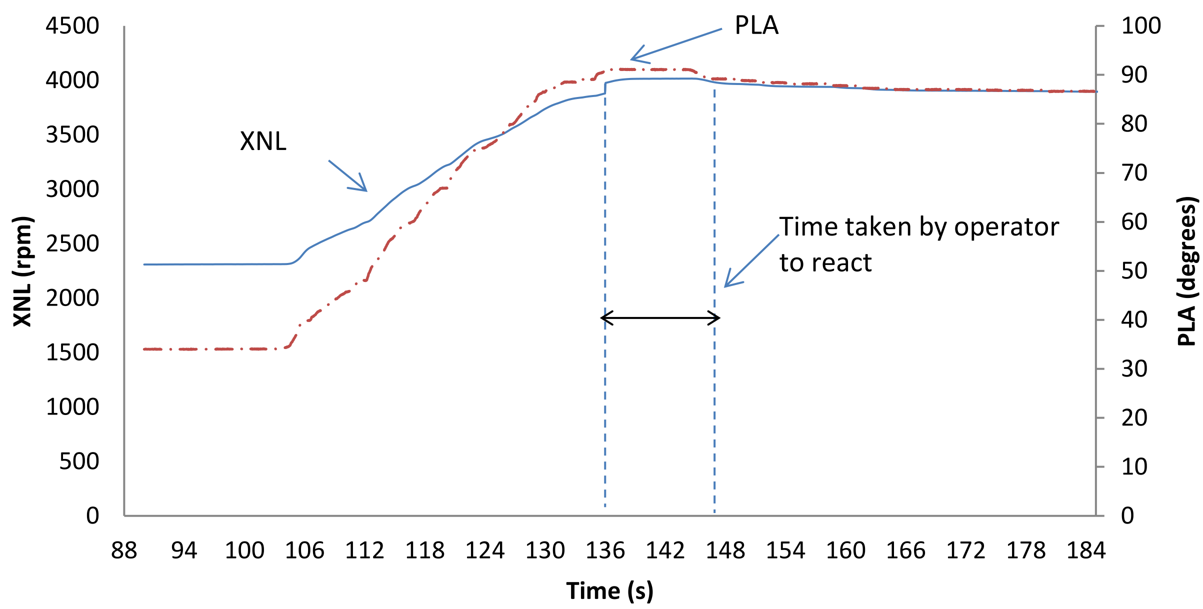

Figure 4-5 Zoom in graph of XNL vs. PLA test 1 for operator 2

It can be easily observed from the graphs that operator 1 took just 3 seconds to bring the XNL back to 3900 rpm and there was prompt reaction from his side but operator 2 took around 12 seconds to bring the condition back to normal.

It was concluded that Operator 1 performed well in the test 1 whereas operator 2 can be trained for this type of emergency situation.

4.2.3 VIBRATION SURVEY TEST WITH EMERGENCY SCENARIO 2

In the second test, the operators were asked to perform the vibration survey test and emergency scenario 2 was introduced in this test. Also in scenario 2, major variable of concern was XNL (low spool speed). The graphs of XNL v/s PLA was plotted for both the operators. While performing these tests the dwell times of the tests were not followed.

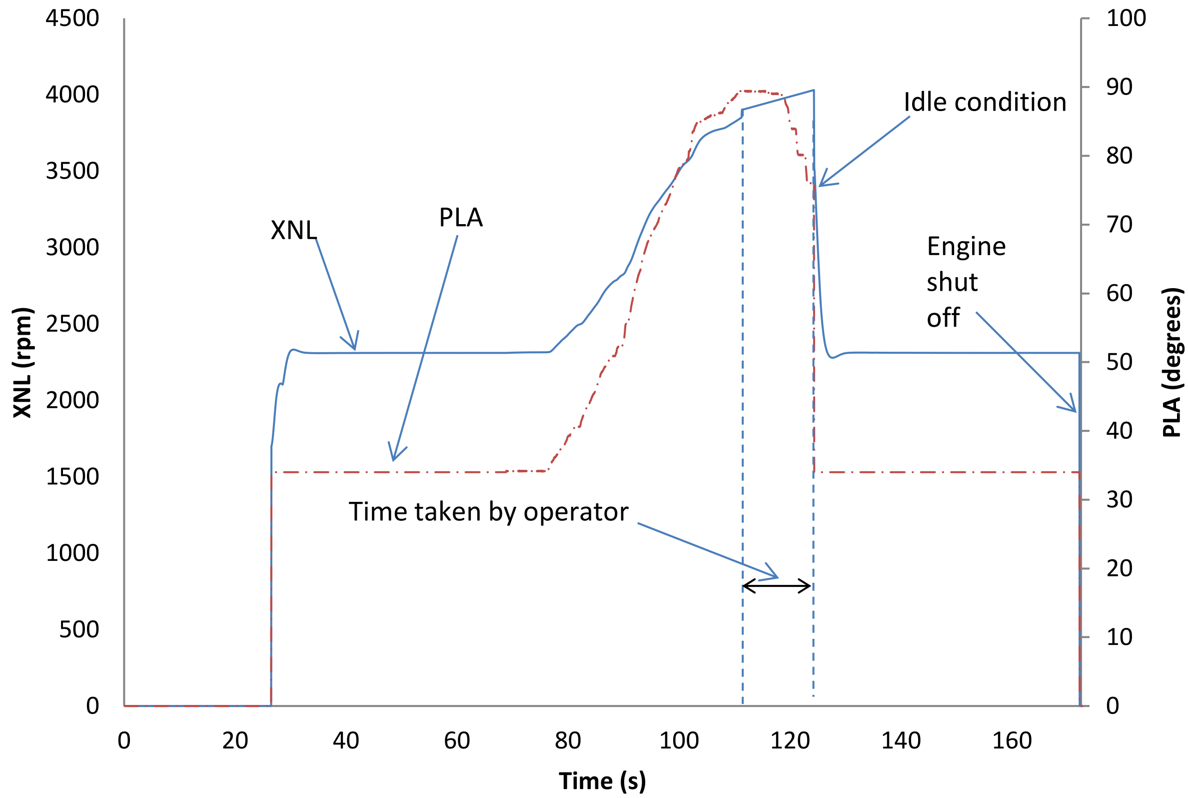

Figure 4-6 XNL vs. PLA test 2 graph for operator 1

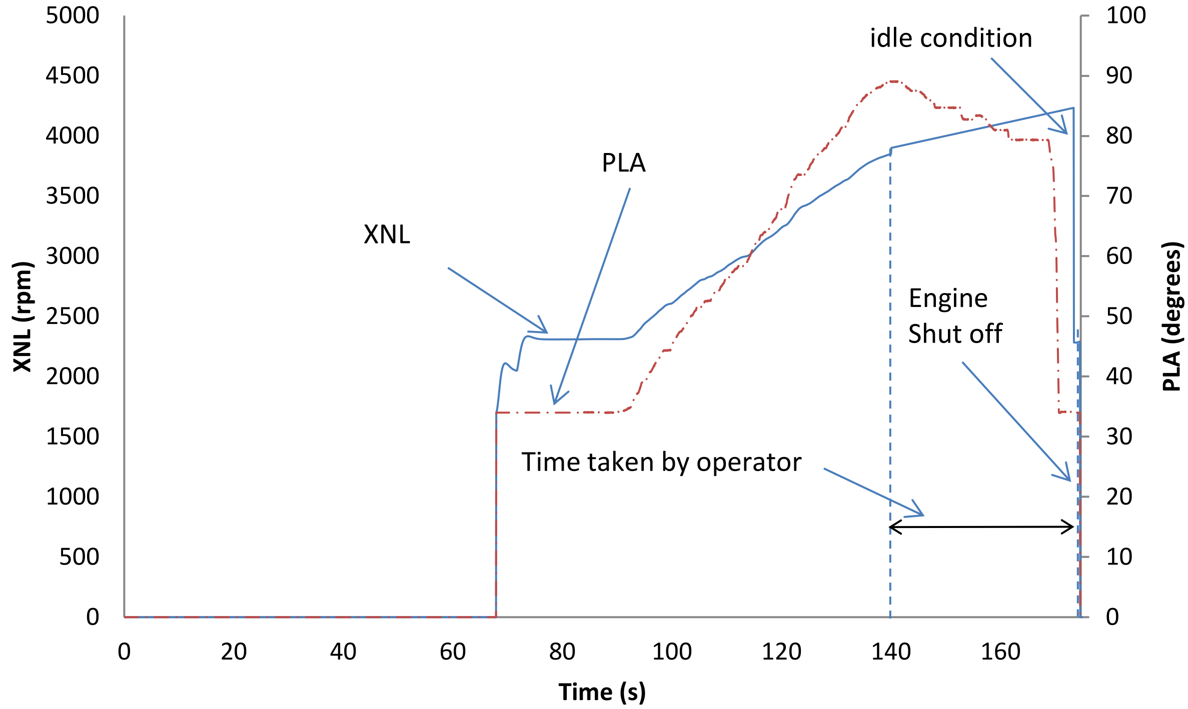

Figure 4-7 XNL vs. PLA test 2 graph for operator 2

In these graphs it can be easily observed that operator 1 reacted quickly to bring engine to the idle condition when he figured out that XNL is out of control and he would not be able to control it with lever. It took him only 5 seconds to pull the right lever to idle condition, but operator 2 took around 30 seconds to bring engine to idle speed.

But as per instructions, the operator had to shut down the engine right after bringing the engine to ground idle. Operator 2 did that perfectly and immediately shut down the engine after bringing engine to idle, but operator1 took around 50 seconds to shut the engine off.

From this test it was concluded that Operator 1 needs training to shut the engine on time, whereas operator 2 needs to react quickly to such type of situations as this can lead to more hazardous conditions at the facility.

4.2.4 POWER CALIBRATION TEST /EMERGENCY SCENARIO 0 (NORMAL)

In the third test, the operators had to perform the power calibration test and emergency scenario 0 (normal) was introduced i.e. no changes in the variables. In this, the system had to react normally and there was no emergency condition. There was no variable of any concern in this test, but still XNL v/s PLA graph was plotted for both the operators. The dwell times were not followed while performing these tests.

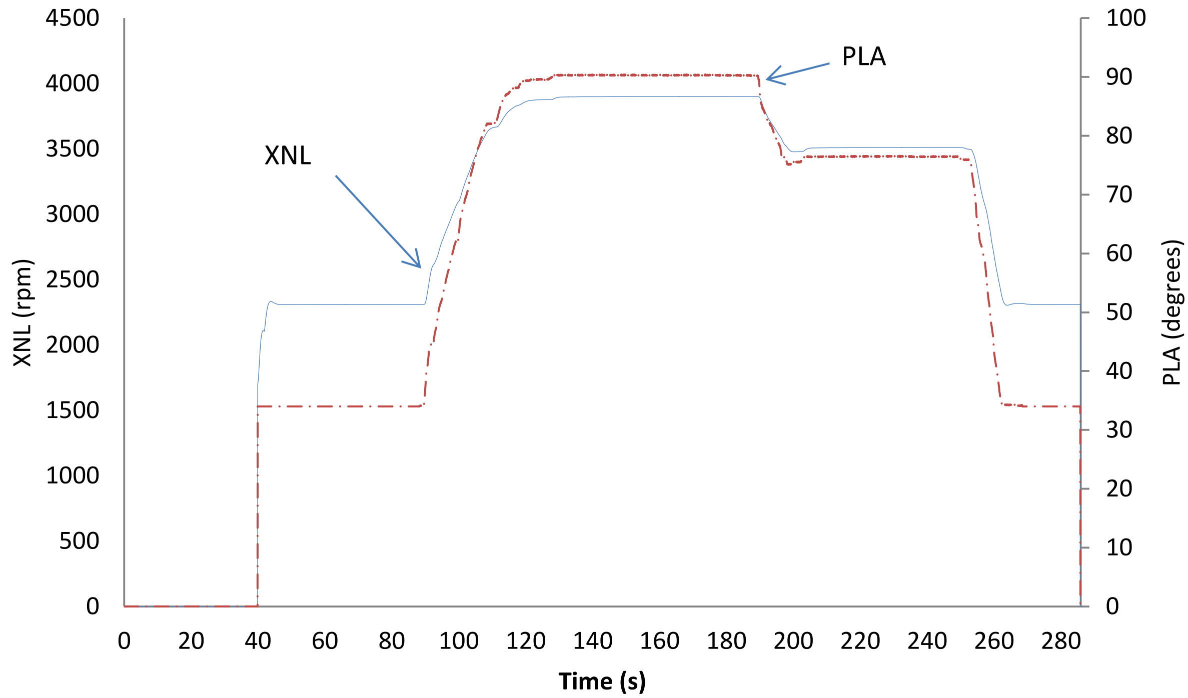

Figure 4-8 XNL vs. PLA test 3 graph for operator 1

In this test scenario, Operator 1 performed it smoothly and completed the test as it was expected. But, operator 2 suddenly pulled the throttle back in order to bring the XNL to 3900 rpm, as he was expecting the increase in XNL. It was concluded that operator 2 needs to be more attentive and should make the changes in PLA only after observing the situation properly, as this could lead to unwanted test results.

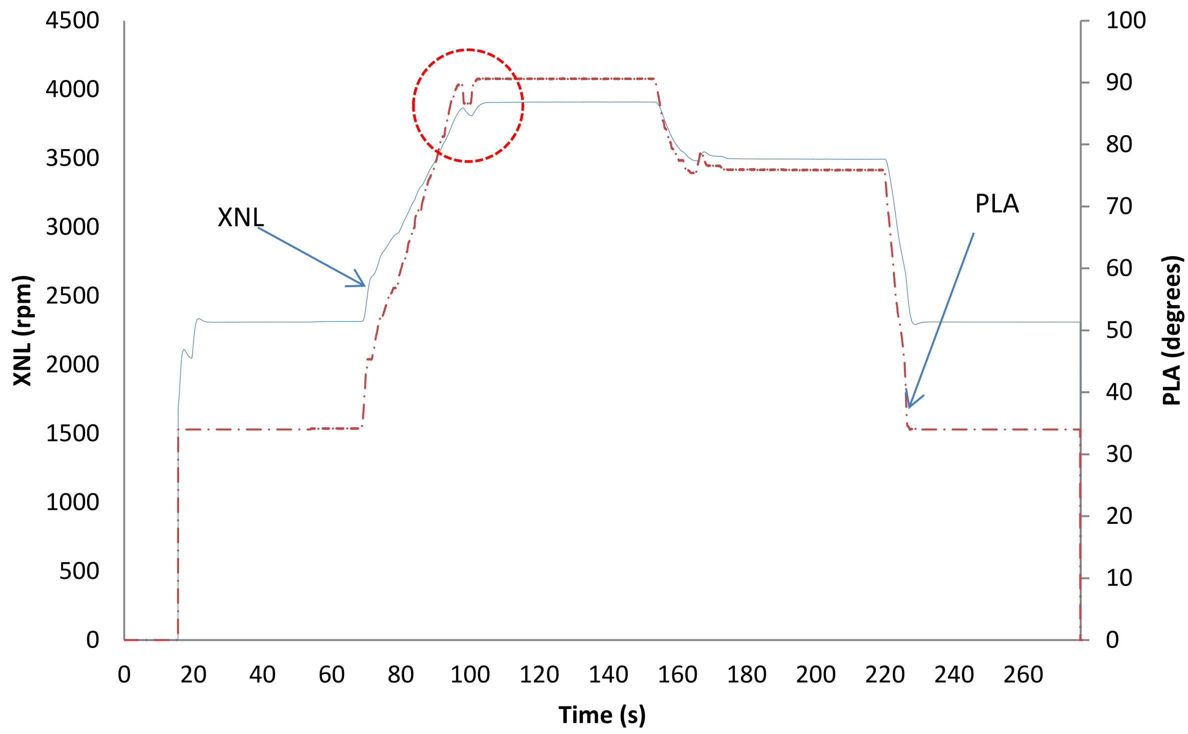

Figure 4-9 XNL vs. PLA test 3 graph for operator 2

4.2.5 Power calibration test with emergency scenario 3

In the fourth test, operators had performed the power calibration test and emergency scenario 3 was introduced. In this scenario there was sudden increase in the exhaust temperature (EGT) at around 1290 °C. In this test, it was expected from both the operators that they will bring the throttle back to the normal EGT. The dwell time was not followed while performing these tests.

In this test the main variable of concern was T4, which is exhaust temperature. T4 v/s PLA graphs were plotted for both the operators and they were closely observed with their reaction.

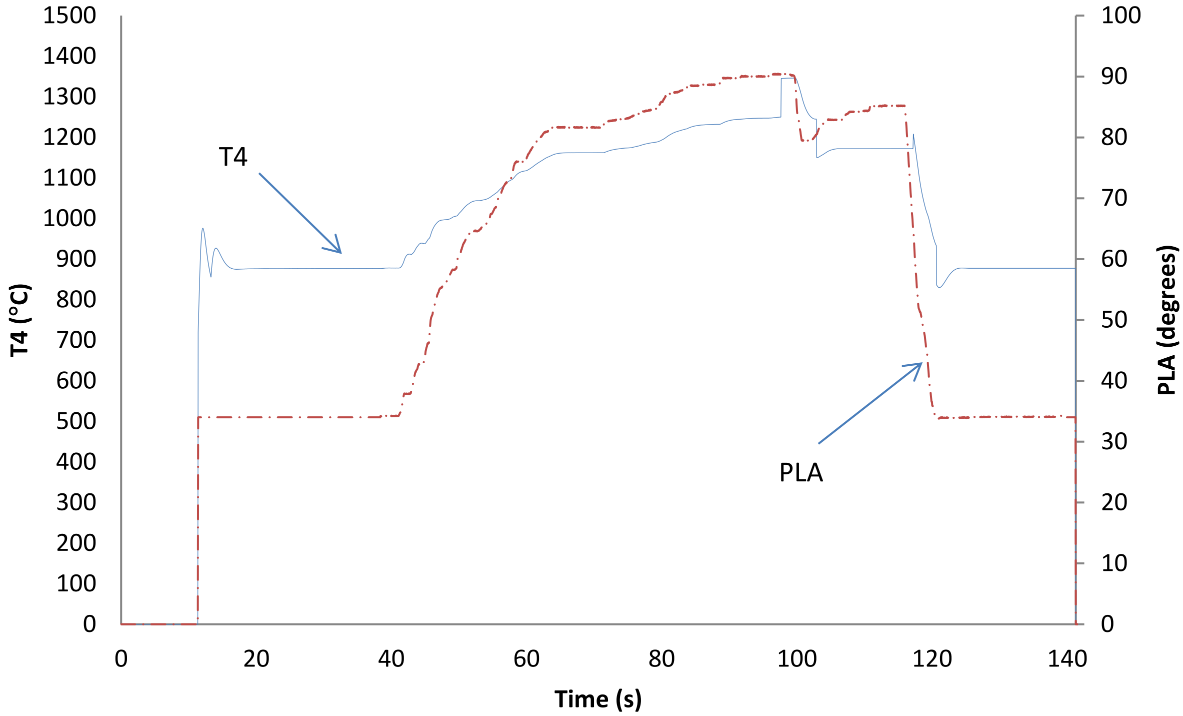

Figure 4-10 T4 vs. PLA test 4 graph for operator 1

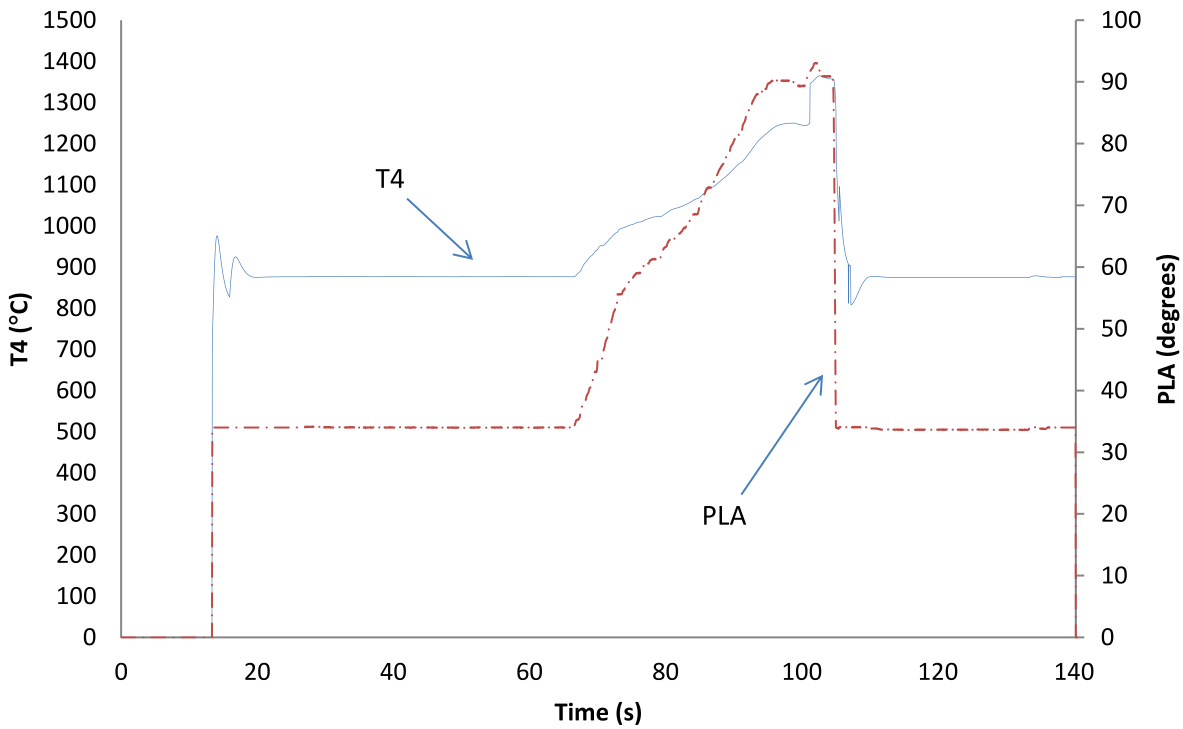

Figure 4-11 T4 vs. PLA test 4 graph for operator 2

To closely analyze the reaction of both operators, the graph was zoomed in and was carefully analyzed.

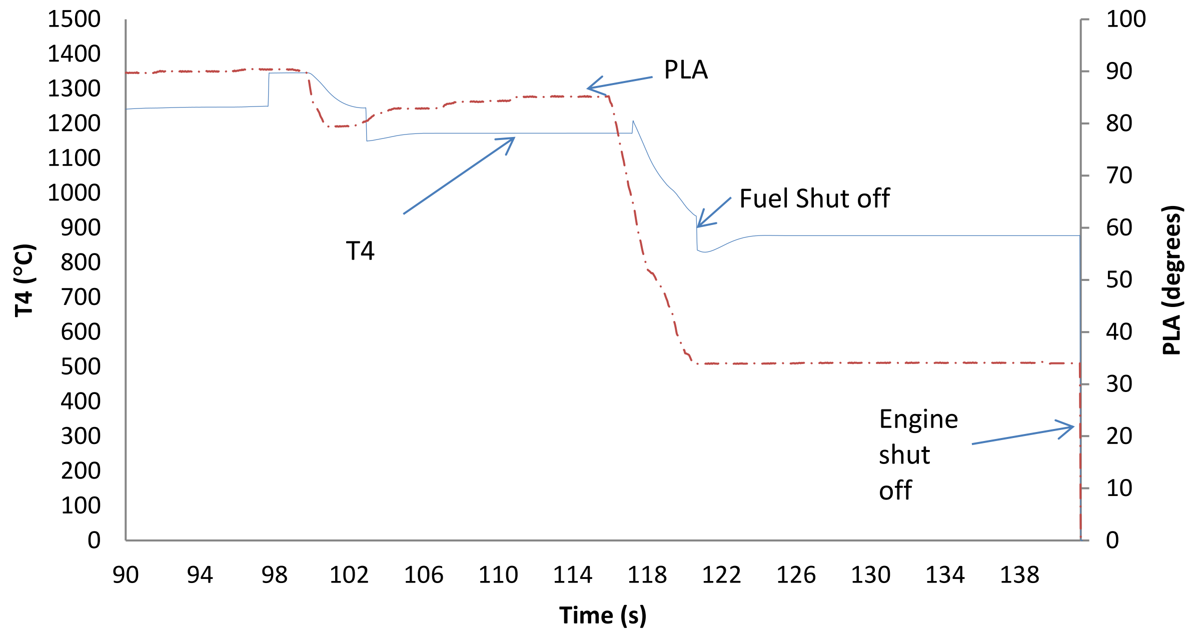

Figure 4-12 Zoom in graph of T4 vs. PLA test 4 for operator 1

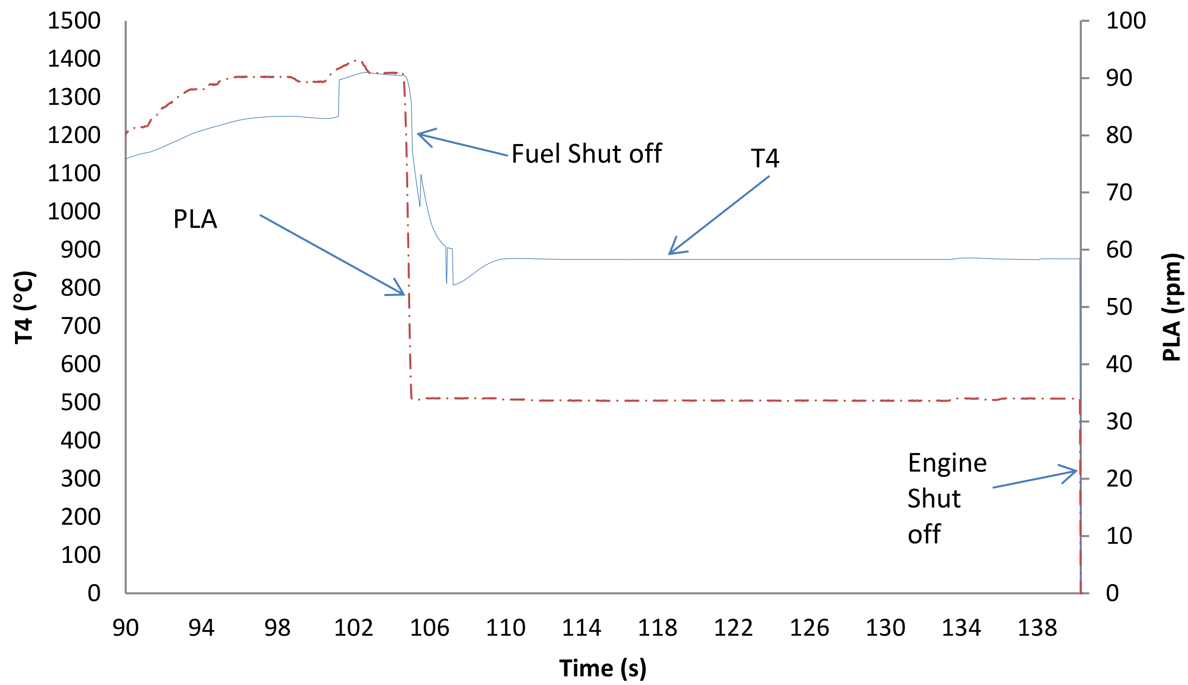

Figure 4-13 Zoom in graph of T4 vs. PLA test 4 for operator 2

From graphs, it can be easily observed that operator 1 tried to bring back the throttle and once the T4 got stable, he tried to complete the test. His first action was to shut off the fuel and then engine but operator 2 got scared of increase in T4 and without bringing the throttle back, he immediately shut off the engine.

It was concluded that operator 2 should be trained for these kinds of emergency situations so that before shutting the fuel he should properly understand the situation.

4.2.6 VIBRATION SURVEY TEST /EMERGENCY SCENARIO 0 (NORMAL)

In fifth test, the operators were asked to perform the Vibration survey test and emergency scenario 0 (normal) was introduced i.e. no changes in the variables. In this the system had to react normally and there was no emergency condition. Since, there was no variable of concern in this test, the XNL v/s PLA graph was plotted for both the operators. The dwell times were not followed while performing these tests.

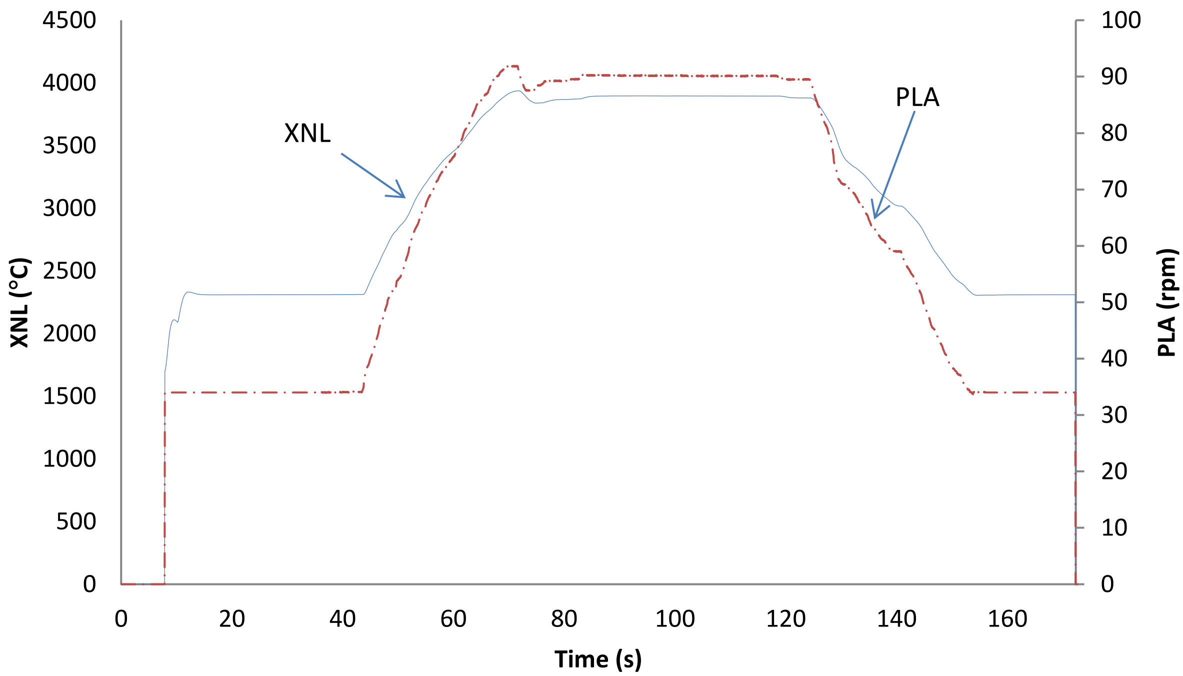

Figure 4-14 XNL vs. PLA test 4 graph for operator 1

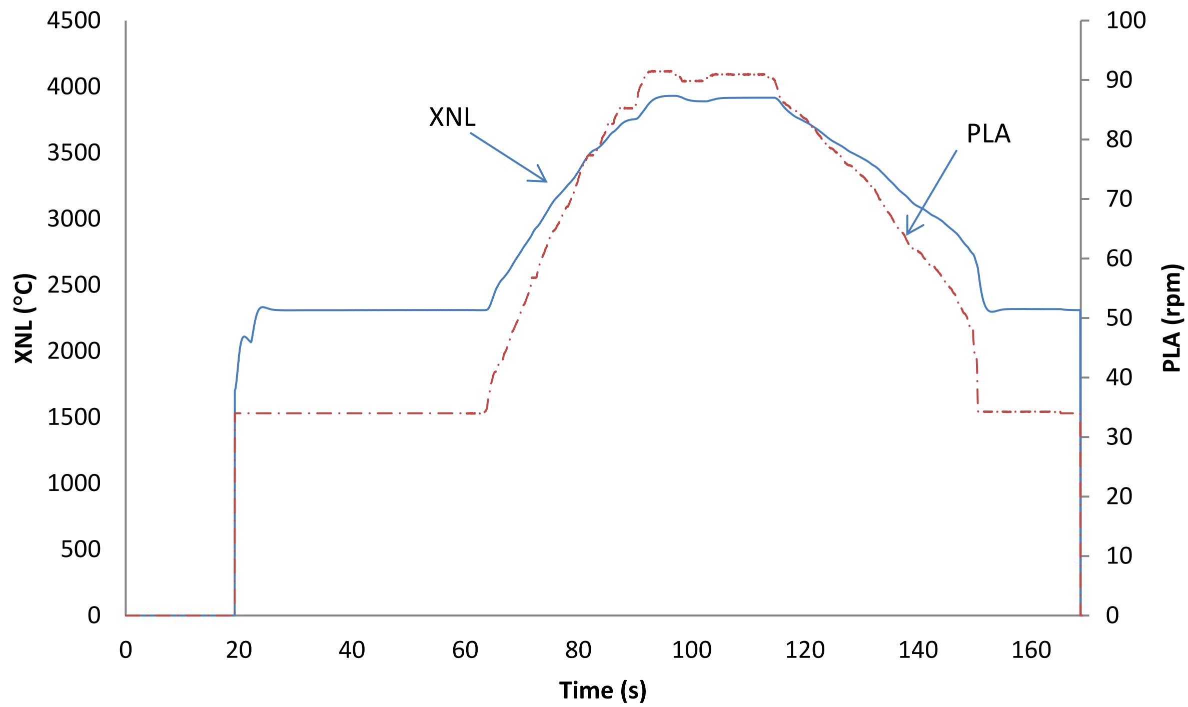

Figure 4-15 XNL vs. PLA test 4 graph for operator 2

On this test both the operators did well. It was expected that they not should react to any of the situation and this is what they did without playing unexpectedly with the throttle.

4.2.7 VIBRATION SURVEY TEST WITH EMERGENCY SCENARIO 4

In test six, the operators performed the vibration survey test and emergency scenario 4 was introduced. In this scenario there was ramp increase in the EGT (T4) which is exhaust temperature at around 1290 °C. It was expected from both the operators that they will try to bring the throttle back, but once they realize that throttle is ineffective, they would pull the right and left lever to ground idle and immediately shut down the engine.

In this test the main variable of concern was T4, which is exhaust temperature. T4 v/s PLA graphs were plotted for both the operators and they were closely observed with their reaction.

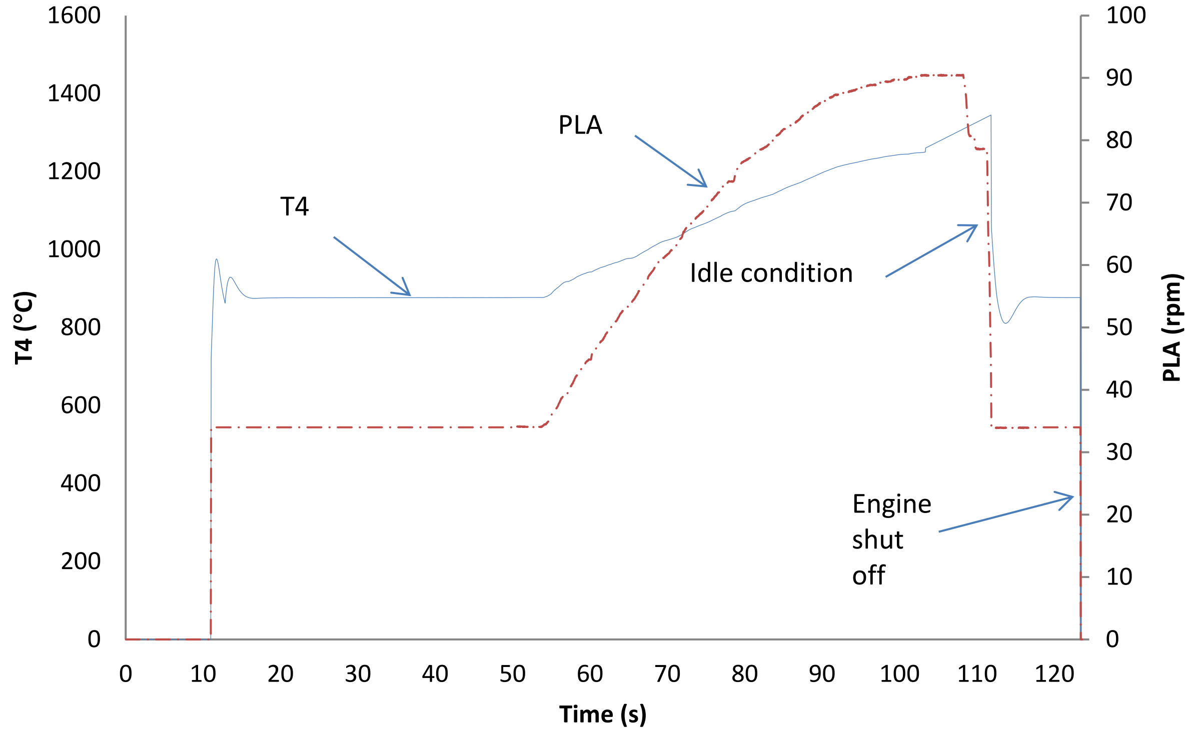

Figure 4-16 T4 vs. PLA test 6 graph for operator 1

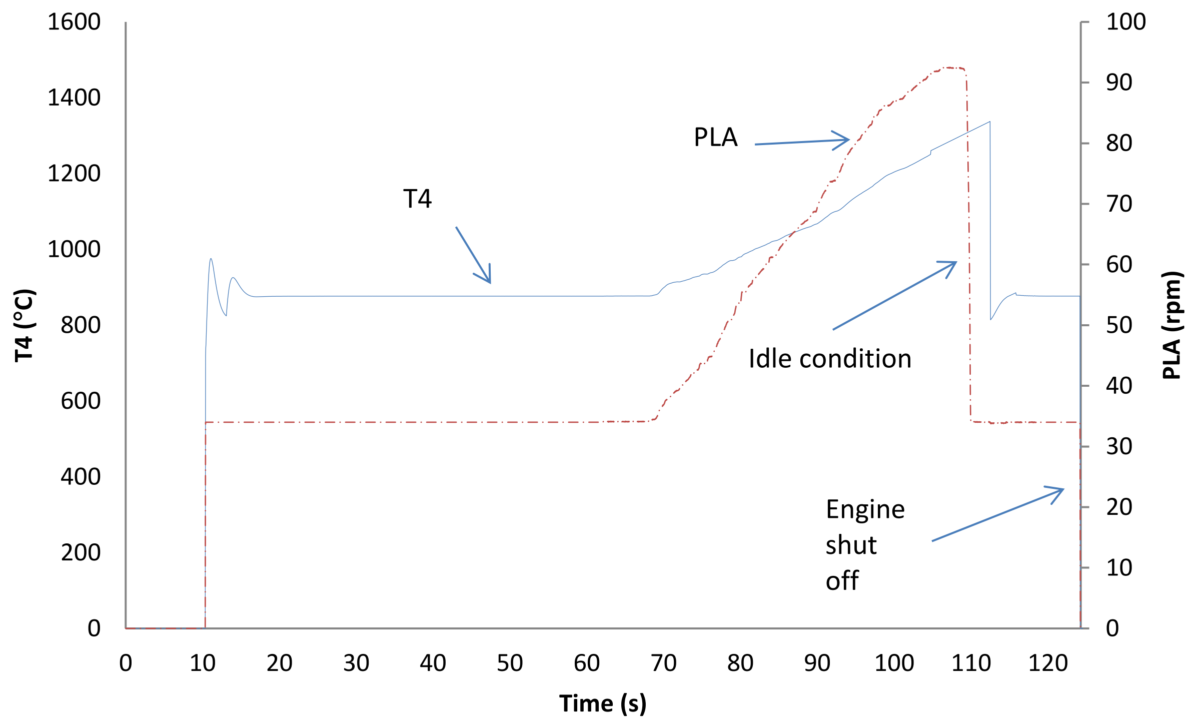

Figure 4-17 T4 vs. PLA test 6 graph for operator 2

It can be easily observed from the graph that Operator 1 tried to bring the lever back, and when he felt that it is unaffected, he pulled the right lever to bring the engine to ground idle and immediately shut the engine off; however, the second operator directly bring the left lever to idle condition without trying to bring the right throttle back. Even though the second operator did well to shut off the engine immediately, he could be trained to pull the right throttle back before pulling the left lever.

Overall, it was concluded that operator 1 performed the tests better than the operator 2 and operator 2 needs more training to improve his performance.

4.3 EVALUATION BY OPERATORS

A qualitative study was conducted for the training simulator, based on the operator's feedback. A questionnaire was prepared (Appendix A1) to get the feedback of operators and based on their experience the operators had to evaluate the simulator. Two operators participated in the survey and the results of that study are shown in Figure 4-18. As observed, the operators agreed that the simulator is useful for the purpose of training for novice operators. Regarding the safety and cost involved in training with simulator, the operators were satisfied with the performance of operator.

In terms of overall experience, there was a broad range of inconclusive opinions. Operators were convinced that they can be trained for more emergency scenarios on the training simulator in comparison to working on the real equipment. Operators also agreed with the fact that an overall knowledge of the working and system is easy to get on training simulator comparatively. The operators wanted to include more variables. They wanted to introduce the ramp effect in temperature and pressures while starting and shutting down the engine.

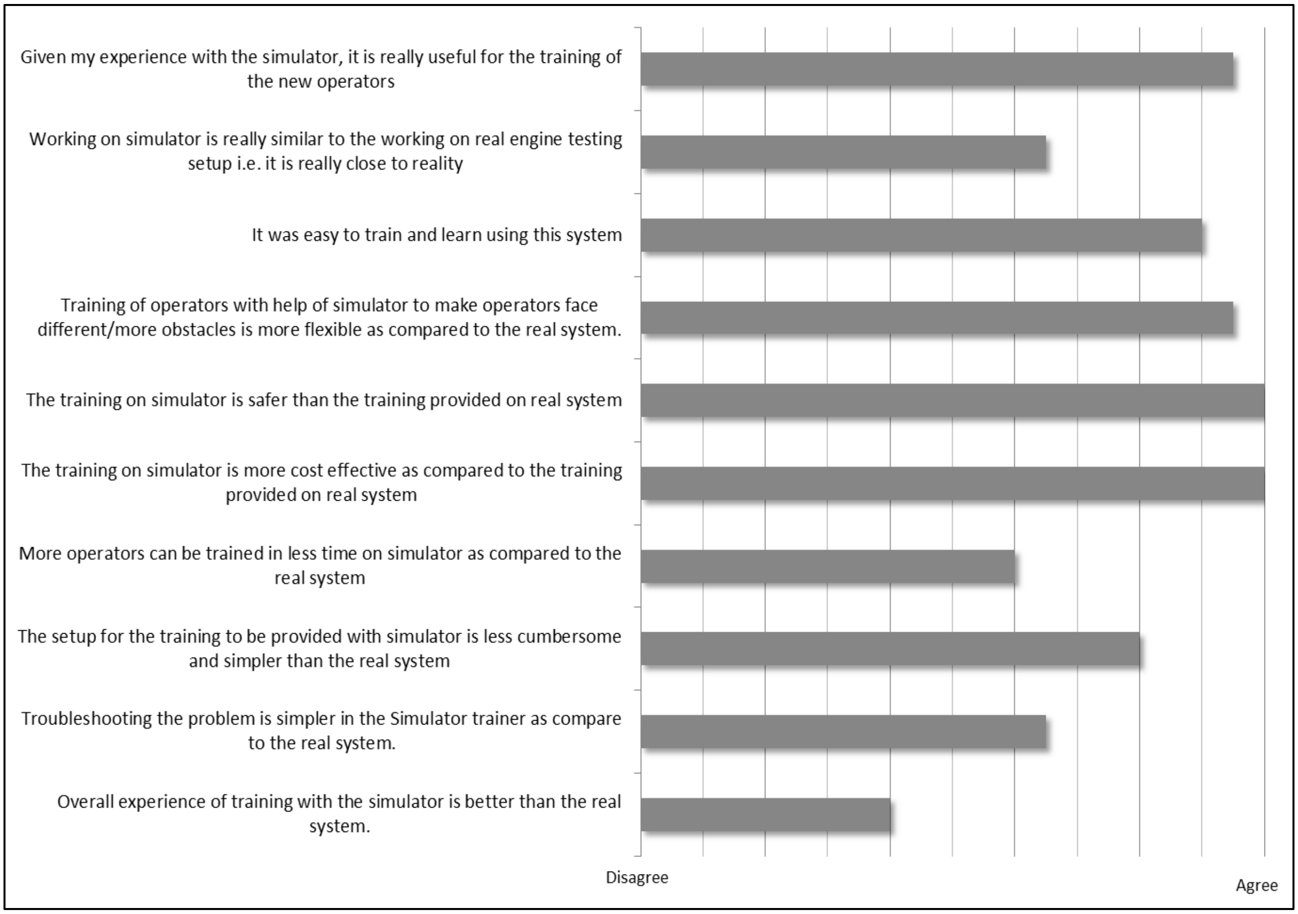

Figure 4-18 Results of qualitative study of training simulator

4.4 SUMMARY

Training simulator for engine testing has been accustomed to facilitate the performance evaluation of the operators. It was observed that the training simulator was able to fulfill the initial needs of the companies associated with the research project by providing the basic training to operators with emergency scenarios involving the change in the temperature and compressor fan speeds of engine.

5 CONCLUSION

5.1 CONTRIBUTIONS MADE IN THIS THESIS

This thesis presented the design and development of training simulator for engine testing operators. The simulator intends primarily to train aviation engine testing operators in a safe and inexpensive simulated environment. Hardware equipment such as throttle lever and control panels were used to deliver input to simulator. Inputs given by operator were scaled to suitable range and processed in model file created with designing software called GasTurb. Model file of jet engine performs real-time calculations based upon design of jet engine and displays the output to operator on user interface created in Unity game engine. An approach was developed to bridge flow of data between Simulink and the model file using second order S-function. Various test scenarios were created based on which operators have evaluated the performance of simulator and its importance for effective training.

Throughout the course of this thesis, clear understanding was developed regarding the requirements of the industries involved to design a training simulator which is flexible and easy to use. For example, now it is easy to switch between different models of engine and it is easy to add more input and output variables. This training simulator can train engine testing operators in safe environment without depending on the weather and availability of engine.

The next contribution made in this work was the design of a training plan for engine testing operators. Different types of emergency scenarios such as random increase in the critical variables of engine were designed and also a method to evaluate the performance of the operators in emergency situation was discussed. However, the challenge was to program these scenarios in

MATLAB, so that it may simulate the real engine problems in real time and operators may follow the same procedure to troubleshoot the problem as they do in the facility. Another major concern was to record the reactions of the operators while performing these tests which can be analyzed later. This helps to give specific trainings to the operators and to make them competent in engine testing. This goal was successfully fulfilled and operators also found this technique effective for the training purpose.

Finally, the simulator was built and qualitatively evaluated by the operators as well as companies involved in the project. Few additions were suggested by the operators which are explained in the future work of this research. Summarising the above points, major contributions in this research are as follow:

i. A training simulator, for aviation engine testing operators that is capable of dealing with the problems associated with the cold engine testing centers was designed, developed and partially evaluated.
ii. An approach is developed to make the training simulator accessing the engine model file in real time with signal delay of 1.05 sec which is not affecting the quality of training simulator and was acceptable by the operators.
iii. The training simulator is flexible to the changes in engine models and output parameters.
iv. The training simulator was designed to train the operators for various emergency conditions.
v. Graphic user interface was developed on the operator side replicating the engine testing facility to provide a real learning experience.
vi. Performance of the training simulator was evaluated by conducting qualitative study based on operator’s feedback.

5.2 FUTURE WORK

There are several suggestions for making this training simulator more realistic. This work can be extended in many ways including, but not limited to, the following subjects:

i. Enhancing the performance of the proposed training simulator by incorporating audible effects and adding more engine variables related to vibration. It is expected that making the simulator more comparable to real equipment will improve the effectiveness of the training and understanding process.

ii. The fault effects were created in this research by programming in SIMULINK which could be replaced by creating the cause in the engine model i.e. no hard coded fault effects should be there. The problem will be generated within the engine model.

iii. The switching of emergency scenarios requires to stop the model and rerun it using different scenario file. Thus, it is desirable to make this training simulator as a complete package which will eliminate the role of trainer and the emergency scenario will be programmed to appear randomly on the operator's side. This will significantly reduce the dependency of the simulator on the trainer, and the simulator would be made capable to switch the emergency scenarios by itself. Additionally, the user interface of simulator can be designed to show the results of the operator's performance, stating the improvements to be done while performing engine testing. It will state what trainings have to be performed to improve the performance and will provide the final score of the operator.

iv. In order to make the training simulator more effective and realistic, more emergency scenarios can also be added. In addition to this, more emergency alerts can be implemented resembling the actual testing facility so that operator may gain the experience of controlling the situation as close as possible to the real setup.

v. The developed training simulator can be upgraded to augment the experience of the operators. The behavior of the variables during the start and shut down of engine can be improved by adding the ramp effect instead of sudden jump in the value of variables.

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7 APPENDICES

A1: Questionnaire

Please rate your experience on using the "Aviation Engine testing cell training simulator". There are no wrong or right answers. We are only seeking your general opinion. Do not put your name on the form.

On each of the following rating scales, please put a cross mark through the line to indicate your assessment. This is an analog scale. This means your answer can be anywhere on the line.
EXAMPLE:
My chances of winning the lottery are:

No Chances at all ________________________ Extremely High

If you thought your chances of winning the lottery were very high, you might place your cross mark through the line as follows:

About 90%
________________________X____

No chance at all Extremely High

1) Given my experience with the simulator, it is useful for the training of the new operators.

Disagree ________________________ Agree

2) Working on simulator is similar to the working on real engine testing setup i.e. it is close to reality.

Disagree ________________________ Agree

3) It was easy to train and learn using this system.

Disagree ________________________ Agree

4) Training of operators with help of simulator to make operators face different/more obstacles is more flexible as compare to the real system.

Disagree ______________________________ Agree

5) The training on simulator is safer than the training provided on real system.

Disagree ______________________________ Agree

6) The training on simulator is more cost effective as compared to the training provided on real system.

Disagree ______________________________ Agree

7) More operators can be trained in less time on simulator as compared to the real system.

Disagree ______________________________ Agree

8) The setup for the training to be provided with simulator is less cumbersome and simpler than the real system.

Disagree ______________________________ Agree

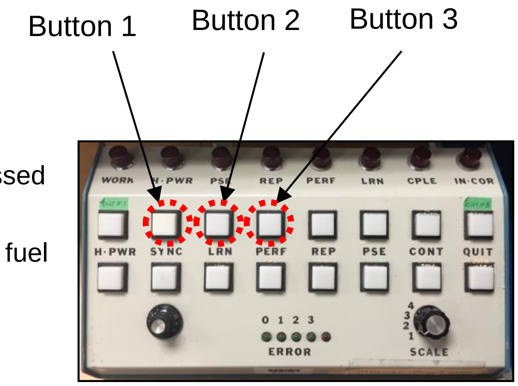
9) Troubleshooting the problem is simpler in the Simulator trainer as compare to the real system.

Disagree ______________________________ Agree

10) Overall experience of training with the simulator is better than the real system.

Disagree ______________________________ Agree

A2: Instruction Material



<u>Introduction to Setup</u>

<u>Control buttons</u>

<u>Button 1 (Air Start)</u> – This button is used to start the engine using compressed air. Then you need to add the fuel to go to the idle position.

<u>Button2 (Emergency Shut off)</u> – This button is used to immediately cut the fuel off and to shut down the engine.

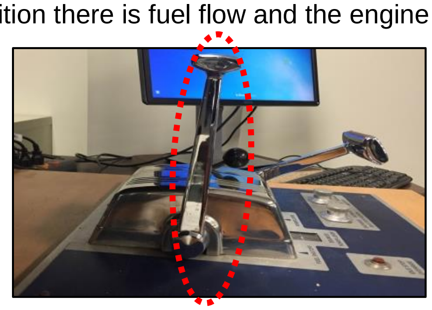
<u>Button 3 (Emergency Motor)</u> - This button is used when the intension is to motor the engine with compressed air without adding the fuel.

<u>Position Lever</u>

<u>Position 1 (Off state)</u> – In this position there is no fuel supply and this is fuel cut-off position.

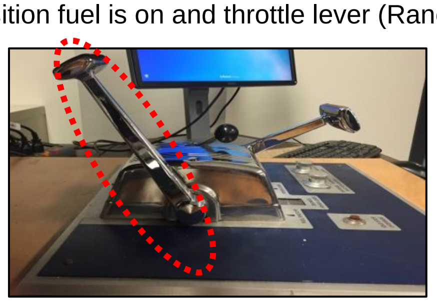
Position 1 (Off State)

<u>Position 2 (Idle state)</u> – In this position there is fuel flow and the engine is at its idle condition.



Position 2 (Idle State)

<u>Position 3 (Run state)</u> – In this position fuel is on and throttle lever (Range from 34 to 103) is activated.



Position 3 (Run State)

Variables on Screen

XNLCT1 - Fan Speed (rpm)

XNHCT1 - Core Speed (rpm)

EGTSL – Exhaust Temperature (°C)

VSV – Variable shutter valve (%)

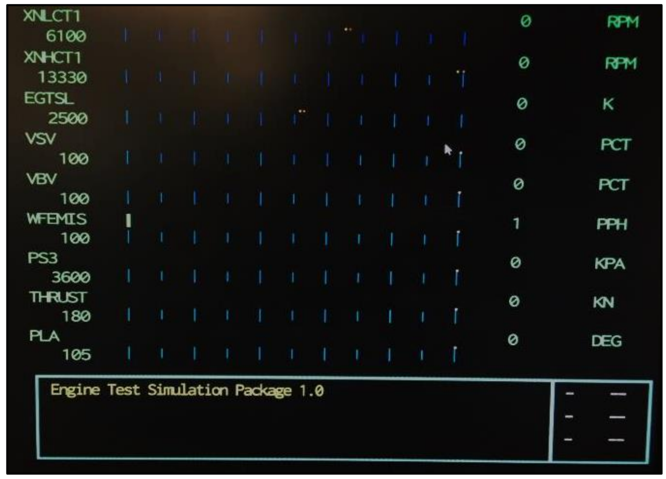
VBV – Variable bleed valve (%)

WFEMIS – Fuel Flow (pph)

PS3 – Exit static pressure (Psi)

Thrust – Thrust of Engine (lb.)

PLA - Power lever angle (Degree)



Auto-Start Operator Procedure

1. **Pre-Start Checks**
   a) Confirm Master Lever Switch is in the “OFF” position
2. **Start Sequence**
   a) Push start button and verify increase in core speed
   b) Once XNL reaches 2047 rpm, move Master Lever Switch to “Idle” position to introduce fuel.
   c) Confirm fuel flow.
   d) Verify engine idle speeds (XNL 2310 rpm, XNH 11761 rpm)
3. **off Idle Operation**
   a) Move Master Lever Switch from “Idle” to “Run” position