University of Cape Town

Development of an Electronic Control Unit for a T63 Gas Turbine

A thesis submitted in partial fulfilment of a Master's degree in Mechanical Engineering.

by

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25 March 2014

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

Acknowledgements

This thesis was a product of the culmination of years of work during which support came to me in many forms. I am unable to list everyone who was integral to the process, and to all those omitted here I must state that my appreciation is no less felt.

My gratitude goes out to SASOL for funding both the project itself as well as the researcher. I hope the developments undertaken ease and assist research both for SAFL and UCT and further inspire new projects. To my supervisor, Prof. Andy Yates, and co-supervisor, Victor Burger, I must give particular thanks. Their supervision was invaluable and without whom this project would never have become a reality. The advice and insight that I drew upon from a stock pile built up over many years of experience was instrumental to making this project possible.

Gerhard Lourens the SAFL technician deserves special mention as he spent many hours assisting with technical glitches and issues.

Special thanks go out to Samuel Ginsberg, Professor Edward Boje and Professor Hennie Mouton for their valuable input.

Glen Newins and his workshop staff for all their assistance and company when things got a bit quiet in the laboratory.

Bruce Raw was the eye of the storm, a calm solid place with plentiful advice and assistance.

And to the Robertson and Raw families, your love and support will forever be cherished.

Declaration

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2. Each significant contribution to, and quotation in, this dissertation from the work, or works, of other people has been cited and referenced.

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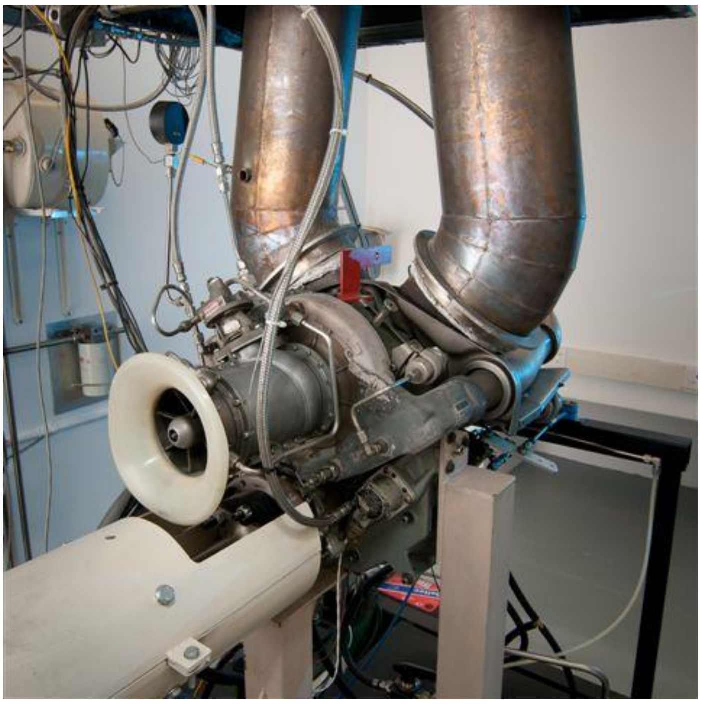
Synopsis

Introduction

Fundamental research has been undertaken at the SASOL Advanced Fuels Laboratory to investigate the effects of the chemistry and physical properties of both conventional and synthetic jet fuels on threshold combustion. This research was undertaken using a purpose built low pressure continuous combustion test facility. Researchers at the laboratory now wish to examine these effects on an aviation gas turbine in service for which "off-map" scheduling of fuel to the engine would be required. A two phase project was thus proposed to develop this capability; the work of this thesis embodies Phase I of that project.



The T63 gas turbine installed on its test bed

The aim of the thesis was to design, build and test an **E**lectronic **C**ontrol **U**nit (ECU) for the Rolls Royce Allison T63-A-700 (hereafter referred to as the T63) gas turbine. It was required that the ECU should allow control of fuel and subsystems so more advanced testing of alternate fuels could be achieved. Knowledge gained during this project was to serve as a foundation for future work to be done which would involve the formulation of a fuel control law. This law would be implemented and tested using the equipment installed over the course of this project.

The Developed Solution

An integrated electronic control unit was developed for the T63 turboshaft engine employing an iterative design philosophy throughout to rework and refine elements before progressing. The ECU comprised of a highly accurate electro-mechanical fuel metering system to give absolute control of fuel scheduling to the gas turbine. This system was linked in parallel with the engine's original mechanical fuel controller such that it was possible to changeover between the two. This provided system redundancy and a failsafe backup in the event of a power or system failure while also permitting comparison of data between the T63's original metering system and the modified system. An electronic throttle actuator was installed to facilitate automation of gas turbine operations. Full automation of the engine was achieved by orchestrating information gained and sent to a variety of sensors and actuators via a Programmable Automation Controller. A graphic user interface, coded in LabVIEW, transmits the operator's commands and provides a means of visually monitoring operations. This user interface also permitted communications to the Schenck dynamometer and throttle actuator granting the use of signal generation capabilities incorporated to promote the future implementation of Phase II of the project. A second host machine running ETA software performed control of the engine's sub systems with two way communications by way of a Programmable Logic Controller. A distributed hierarchal hardware infrastructure was employed to give a central management point and distribute processor load. The two host machines were accessible from a single point and log data acquired during testing in duplicate.

Commissioning

An incremental methodology was followed when undertaking commissioning of the ECU. Each element and component of the design was tested and fine-tuned with additional functionality included in each successive run. A theoretical model of the gas turbine cycle was used to complement the experimental measurements. Also a modelling calculation was used to derive the theoretical combustion stability envelope from which the thermal implication of a combustion flame-out could be evaluated.

Tests run during commissioning led to an alteration of the procedure for operating the engine. The operation mode in which the dynamometer was run was also modified. The result of these changes was an improved system performance in terms of dynamic stability and response. Safety systems were tested to ensure functionality thereof and to examine the engine's response to activation of these devices. Comparisons were made of the effectiveness of manual versus automatic throttle actuation to highlight the benefits of the changeover. Automation was first achieved with the ETA software though the PLC and tested to define parameters and optimal automation sequencing for implementation in the final LabVIEW controller. At the conclusion of the commissioning and refinement process it was ascertained that the LabVIEW automation system functioned in a reliable manner over the full range of engine operations. The performance of three engine excitation options was investigated for application during the future system identification portion of Phase II of the project. Results showed sinusoidal testing utilising the signal generation capacity of the developed system to be both possible and the most promising option.

Conclusions and Recommendations

A systematic approach was taken to the design problem and an iterative methodology applied to produce an electronic control unit which proved to be a successful amalgamation of both hardware and software. The ccompleted device consisted of redundant fuel control system with a hybrid design (mechanical & electronic controllers) and a software based controller. The ECU fulfills the user specifications achieving greater precision, accuracy and repeatability than originally possible. The system that has been developed provides a high degree of re-configurability with source code that is well documented and fully accessible hence aiding future evolution of the device. The change in the standard operating procedure of the engine resulted in improved engine performance while the change in control mode of the dynamometer allowed for inherently safe and significantly more stable operation. This project confirms the viability and lays the foundations for future development in Phase II of the project.

Some improvements must be recommended for certain of the engines sub-systems. One such enhancement would be the alteration of the Bypass Valve located in the oil lines of the Power Take-off system. This valve must be continually adjusted to account for pressure changes as the oil heats up and cools down to diminish the possibility of oil transfer between the Main Engine Oil tank of the test cell and the Power Take Off tank. The second sub-system revision should be the replacement of the oil cooling unit. It became apparent during testing that the oil cooler is insufficient for operations where application of load is above 180 Nm when operating the dynamometer in speed control mode.

Overall this project forges the first step towards attaining the end goal -endowing the researcher with a means to alter fuel scheduling at will. Thus enabling further investigation to determine the extent to which the chemistry of a fuel and its physical properties influences threshold combustion.

Development of an Electronic Control Unit for a T63 Gas Turbine

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Nomenclature & Acronyms

ACK	Acknowledge
ADC	Analogue to Digital Converter
AI	Analogue Input
AMB	Ambient conditions
AO	Analogue Output
CAN	Controller Area Network
CIT	Compressor Inlet Temperature
CP	Collective Pitch
CPU	Central Processing Unit
CRC	Cyclic Redundancy Check
cRIO	Compact RIO
DAQ	Data Acquisition
DC	Direct Current
DECU	Digital Electronic Control Unit
DLC	Data Length Code
EASA	European Aviation Safety Agency
ECU	Electronic Control Unit
EOF	End of Frame
EPR	Engine Pressure Ratio
FAA	Federal Aviation Administration
FADEC	Fall Authority Digital Engine Control
FCU	Fuel Control Unit
FPGA	Field Programmable Gate Array
FPU	Fuel Pump Unit
FTP	File Transfer Protocol
GUI	Graphic User Interface

HMU	Hydro Mechanical Unit
IDE	Identifier Extension bit
IFS	Inter Frame Space
I/O	Input/ Output
$\boldsymbol{k}$	Proportional Gain Constant
LA	Lever Angle
LDS	Load Demand Spindle
LED	Light Emitting Diode
LPV	Linear Parameter Varying
LVDT	Linear Variable Differential Transformer
$\boldsymbol{M_T}$	Torque Pressure Sensor
MBC	Multi Bus Card
MGT	Measured Gas Temperature
$\dot{m}_{\boldsymbol{fuel}}$	Mass Flow Rate of Fuel
$\boldsymbol{N_1}$	Speed of Low Pressure Compressor Spool (also $\boldsymbol{N_G}$)
$\boldsymbol{N_2}$	Speed of High Pressure Compressor Spool (also $\boldsymbol{N_P}$)
$\boldsymbol{N_R}$	Speed of Rotor System
NI	National Instruments
OEM	Original Equipment Manufacturer
$\boldsymbol{P_{F0}}$	Fuel Supply Pressure
$\boldsymbol{P_{F1}}$	Pressure of Fuel after Fuel Pump
$\boldsymbol{P_{F2}}$	Pressure of Fuel after Metering Valve
$\boldsymbol{P_0}$	Ambient pressure (also $\boldsymbol{P_{AMB}}$)
$\boldsymbol{P_{AF}}$	Pressure after Filter
$\boldsymbol{P_{BF}}$	Pressure before Filter
$\boldsymbol{P_C}$	Compressor Discharge Air Pressure ((also $\boldsymbol{P_{CD}}$)
$\boldsymbol{P_F}$	Feedback Pressure

P_G	Pressure to the Governor Line
P_M	Modulated Pressure
P_N	Fuel Outlet Pressure
P_{OS}	Pressure to Overspeed Valve
P_R	Regulated Pressure Line
P_W	Pressure to the Windmill Bypass
P_X	Pressure over the Sealed Acceleration Bellows
P_Y	Pressure over the Differential Bellows
P_{COM}	Pressure over the Combustor
P_{Fuel}	Pressure of Fuel
PAS	Power-Available Spindle
PCI	Peripheral Component Interconnect
PID	Proportional-Integral-Derivative Controller
PLA	Power Lever Angle
PLC	Programmable Logic Controller
PMA	Permanent Magnet Alternator
Pro E	Pro Engineer
PRS	Product Requirement Specification
PSU	Power Supply Unit
PTO	Power Take-Off
PWM	Pulse Width Modulation
QFD	Quality Function Diagram
r0	Reserved Bit
RIO	Reconfigurable Input/ Output System
RTR	Remote transmission request
SAFL	Sasol Advanced Fuels Laboratory
SISO	Single Input Single Output

SOF	Start of frame
T_{CI}	Temperature at Compressor Inlet
T_{CL}	Temperature of Combustor Liner
T_{EX}	Exhaust Temperature
T_{Fuel}	Temperature of Fuel
T_{Oil}	Temperature of Oil before Cooling
$T_{Cooled\ Oil}$	Temperature of Oil after Cooling
TDMS	Technical Data Management Streaming
TIT	Turbine Inlet Temperature
TOT	Turbine Outlet Temperature
UCT	University of Cape Town
VI	Virtual Instrument (LabVIEW program/subroutine)
W_f	Fuel flow
WBS	Work Breakdown Structure

Standard Engine Station Numbering:

0	Ambient conditions
1	Engine intake front flange, or leading edge
2	Compressor face
3	Compressor exit face
4	Combustor exit plane
5	Last turbine exit face

1. Introduction

In all internal combustion engines the requirement to regulate the power output is effectively achieved by controlling the fuel supply to the engine. However there is a further requirement to maintain the fuel-air ratio within the envelope imposed by the combustion system and the ever increasing emission constraints. The fuel control system is arguably the most precise and complex component at the heart of all engine types. In the case of the aero gas turbine, the system control difficulties are further compounded by the fact that the engine has to function reliably over a very wide range of extreme ambient conditions. The operation of these gas turbines is a complex task involving many repetitive mechanical operations. If these machines are to operate at the height of their performance and efficiency controllers that are able to manage duties beyond the capabilities of humans are a prerequisite.

1.1. Control of Gas Turbines

For the gas turbine engine to function at the optimal level, control systems are required to monitor engine operations and maintain fuel flow at the desired levels. The fuel metering systems traditionally took the form of **H**ydro **M**echanical **U**nits (HMU). HMU's are used to implement simple but robust control schedules that affect the fuel flow to the engine. Due to the resilient design of these hydro mechanical devices they continue to be used in modern helicopters providing backup systems in the event of electronic failure. The 1980's saw the implementation of the **E**lectronic **C**ontrol **U**nit (ECU) as the primary control system in some of the more advanced rotorcraft. Continual development and improvement within this field has led to the ECU being employed in all present day helicopters resulting in improved efficiency and performance. [1]

Feedback control is utilized in the ECU to maintain the function of the engine close to the mechanical, thermal and pressure limitations while ensuring safe operating conditions. A number of sensors and actuators are employed throughout the engine to monitor conditions and effect control over various devices allowing a high loop gain to be achieved. Of these sensors the most common to be used to control the system are the turbine speed and pressure sensors while thermocouples are used to monitor temperature within the engine [1]. Figure 1 shows the layout of a typical control system employed in present day rotorcraft.

Controllers employ **S**ingle-**I**nput-**S**ingle-**O**utput (SISO) systems, designed via pole placement techniques, to move fuel metering valves thereby regulating turbine speeds or pressure ratios to a more accurate degree than was previously possible thus expanding the operational range. [2], [3]

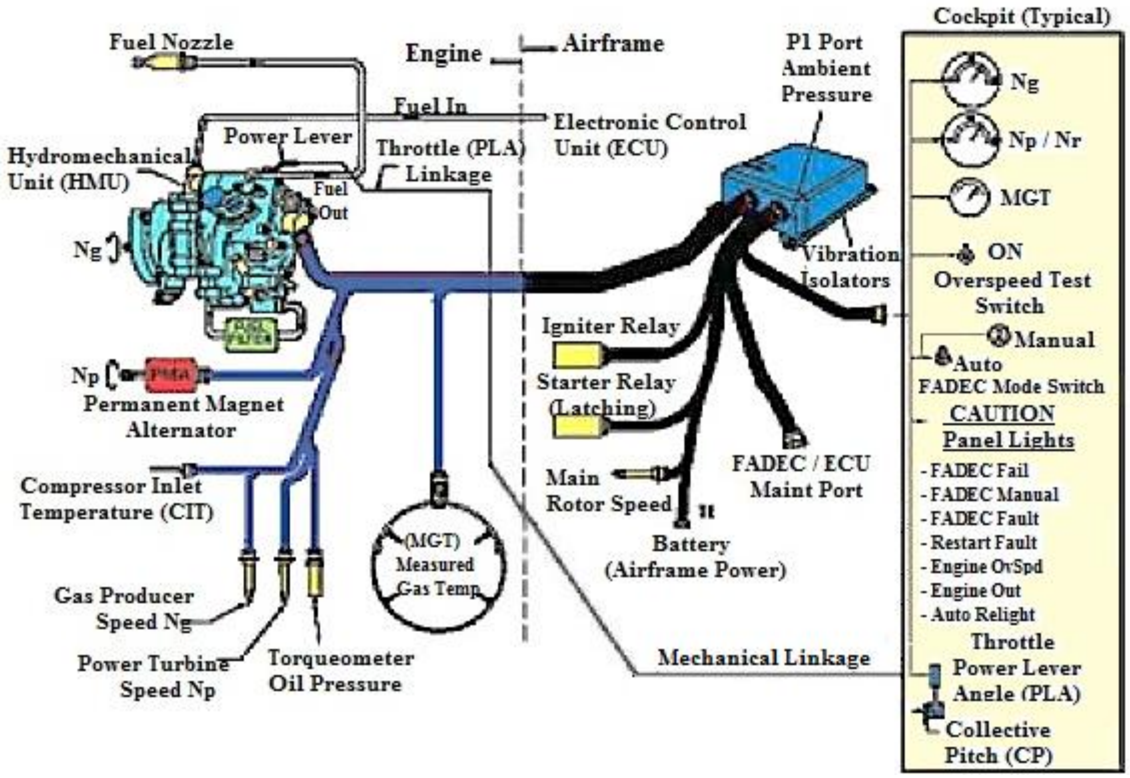


Figure 1: Control system arrangement for Rolls Royce Model 250 C30R/3 [4]

1.2. Context of Project

A Rolls Royce Allison T63-A-700 Gas Turbine was commissioned for use in the Mechanical Engineering department of the University of Cape Town as part of a Masters project in 2008. The engine has been used to undertake testing of various conventional and alternative jet fuels. The engine is popularly used in research due to its widespread application in the aviation industry and was originally selected for use at the **S**asol **A**dvanced **F**uels **L**aboratory (SAFL) due to the accessibility of the combustor and the relative low cost of the engine which maintained affordability [5].

Semi-synthetic jet fuel has been successfully used for commercial flights from Johannesburg since 1999 and in 2008 fully synthetic jet fuel received approval, under the British Ministry of Defence Standard 91-91, for commercial use by airlines [6]. Further development of alternative jet fuels driven by ever increasing pressure caused by depleting oil reserves and environmental impact concerns has increased the need for improved research with regards to performance parameters of these fuels and their effect on the engines that are currently in commercial use.

Future plans for the test engine at SAFL involve a redesign of the rich primary zone combustor so as to maintain the validity of testing for both the present and future. This combustor will be upgraded to a lean primary zone combustor thus the engine will need to be remapped from the original operating parameters. The need for an electronic fuel control unit has therefore emerged. The aim of this project was to first determine the feasibility of the creation of a digital controller, for the gas turbine, capable of "off map" fuel scheduling. The hardware and software that would form the infrastructure of an ECU were then to be developed. Knowledge gained over the duration of the project was to serve as a foundation for a follow up project which would involve the formulation of a fuel control law that could be then be implemented and tested using the equipment designed over the course of the initial project. The ECU was to be designed to enable governing of fuel flow to the engine as well as monitor operations and impose safety limits. This would enable the engine to be run off the normal operating line and permit tests to be carried out at the combustion thresholds.

The engine installed in 2008 was controlled by the hydro mechanical unit originally designed for this gas turbine. An in depth review of this unit appears in Appendix A and includes detailed diagrams of each of the systems discussed herein.

The HMU comprised of a fuel supply unit that pumped fuel to the system at a sufficient rate and pressure. The fuel flow rate was scheduled as a function of the compressor discharge pressure (P_C), the Gas Producer (N_G) and Power Turbine (N_P) speeds and lever angles.

Fuel to the engine was metered out by means of a valve, the position of which is adjusted by the Gas Producer governor and acceleration bellows operating together. The Power Turbine governor engages an assortment of cams, springs and flyweights to reset the fuel control schedule thereby altering the speed of the Gas Producer as well as preventing overspeed of the spools.

This control system maintained fuel flow rate thereby sustaining combustion and engine power production. It also protects the engine N_G spool by preventing overspeed as well as of the N_P spool through sustained 100% speed operation.

It is possible that engine damage may be sustained if the **T**urbine Inlet **T**emperature (TIT) or the torque limits are exceeded. On the originally installed system there was no direct feedback control of engine fuelling and therefore it was the responsibility of operator to prevent this damage. Other limits that require careful monitoring are related to fuel and oil supply to the engine. Each of these has sensors transmitting information about the flow rate, temperature and pressure such that they may be monitored and kept within defined limits to prevent damage to the engine.

Certain modifications were added to the test bed to make amends for particular conditions that prevailed due to the nature of the set up. One such modification was the addition of a controlled bleed on the P_R line of the fuel control system that could be used to reduce oscillations in engine speed. This compensated for the low rotational inertia produced by the eddy current dynamometer which was used to simulate in-flight loading on the engine.

Recommendations to improve the gas turbine installation were put forward. The first advised that engine speed oscillations should be under better dynamic control. An upgrade to the engine control in the form of an electronic throttle controller was suggested. The throttle would be required to vary the N_P lever according to load thereby making transient cycle testing possible and affording better engine protection. It was also proposed that better TOT gauge accuracy be obtained.

1.3. Project Scope

The primary focus of this dissertation project was the design, development and construction, of the necessary hardware and software required to create the ECU. Installation and commissioning of the entire system was to be performed as well as to ensure its suitability to implement a control law devised in Phase II of the project.

1.4. Plan of Development

The report is structured such that it commences with a review of literature covering a number of existing systems most relevant to this dissertation project. An overview of control and related theory is then carried out, followed by an in depth study of the original fuel control system of the T63. Subsequent to this is a chapter covering identification of the design requirements and planning procedure, detailing the baseline testing and conceptual design phase. The report then proceeds with a review of the design of the final product including development of the electro-mechanical system and digital systems including the architectural layout of the hardware and software required. This is followed by a look into the software programming and implementation. The process undertaken to commission the ECU is then documented, noting results and observations obtained. Findings made during the course of the project are summarised and conclusions drawn from these. Recommendations are then formulated drawing to note various improvements that might be made. A section describing the original subsystems of the T63 leads in the attached appendices. This is followed by sections covering the detailed design of the digital systems and an appendix containing specifications for the ECU. Remaining appendices feature planning aids employed over the course of the project and comprehensive material documenting standard operating procedures for the developed systems.

2. Literature Review

Since the inception of the gas turbine there have been many varied control systems have been implemented to control different aspects that affect the engine's performance. One of the most complex of these devices is the **F**uel **C**ontrol **U**nit (FCU) of which there are two main types: hydro-mechanical and electronic. Hydro-mechanical control is traditionally the more frequently used of the two options while some of the more advanced engines make use of a mixture of the two systems under control of an ECU or **F**ull **A**uthority **D**igital **E**ngine **C**ontroller (FADEC). [7]

This section of the report investigates a number of engine controllers in which these aforementioned systems are found, focusing on the control methods implemented and actuation options for implementation of the control system.

2.1. Model 250-C30R/3 Fuel System

The first fuel system investigated was that of the Rolls Royce Model 250-C30R/3, an engine that was the big brother of the T63 and possessed many similarities. This system provided the nearest existing commercial representation of what was to be achieved in this project.

The T63 version of the Rolls Royce Allison gas turbine was originally designed as part of a joint venture with the American military. Its first official run was in March 1961 and by the end of the 1980's sales of the military and civilian versions of the engine dominated the light turbine helicopter market. [8]

Over the years a large number of improvements to the engine were required so as to meet new needs as missions became more complex and demanding. Eventually the Series IV C30R/3 engines were installed in the Kiowa, which gave not only additional power but were controlled with a FADEC created by the Goodrich Engine Control Systems division [9]. The civilian variant of this controller is found in the Model 250-C40B and C47B engines [4].

The FADEC system installed on the C30R/3, the EMC-35 is a hybrid system which consists of two main components these being the ECU and Hydro-Mechanical Unit. The ECU maintains control of the system by monitoring and controlling engine parameters such as the engine speed, fuel flow, rate of acceleration, temperature and torque. Another capability that the FADEC possesses is its ability to detect flameout and its ability to relight. The N_G gear train drives the HMU which meters the fuel while maintaining the correct fuel pressure. [4], [10], [11]

If the ECU is disabled for any reason the HMU functions manually limiting the fuel flow as a function of the **P**ower **L**ever **A**ngle (PLA). A schematic depicting the transition from automatic to manual functioning is shown in Figure 2. In manual mode the two pistons are engaged and move in accordance with throttle position via the Power Lever Shaft. A gear on this shaft meshes with another that is attached to a collar that wraps around the manual piston. The collar can then be rotated to reveal a hole on the piston when the piston moves to the left or right. The loading piston keeps the metering valve lever against the face of the manual piston. Manual mode also ensures the igniters are continuously energised thus aiding to prevent flameout. [12]

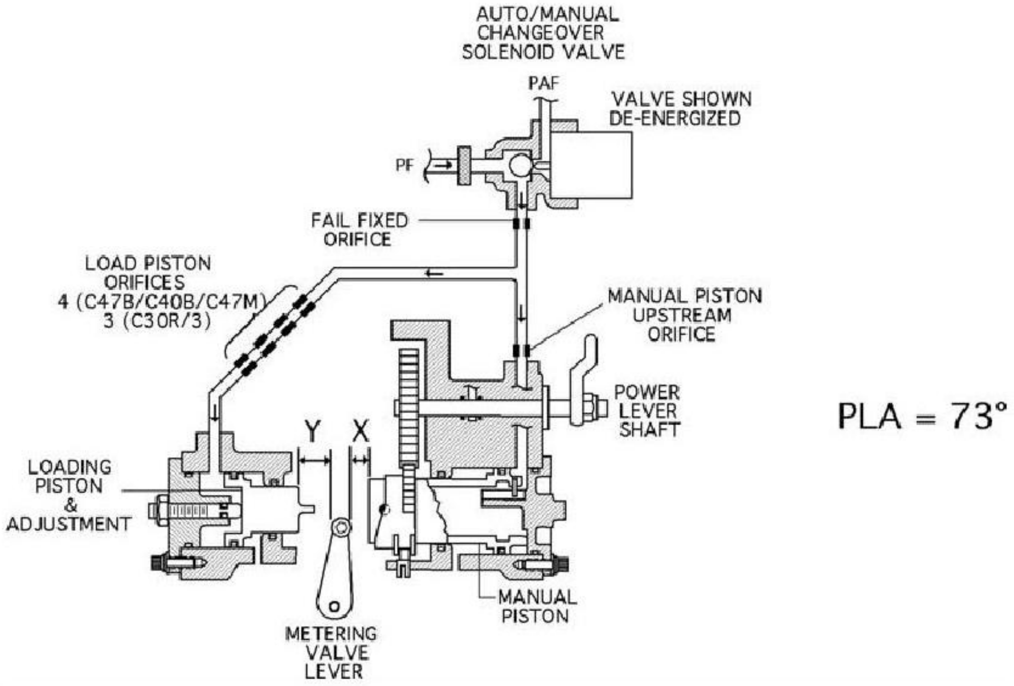


Figure 2: Automatic to manual transition [12]

The gearbox of the C30 contains within it two dual winding monopole pickups, used to measure the gas producer and power turbine speeds. The readings from each of these pickups are passed on to the engine ECU providing a closed feedback control loop. [10]

Engine speed of both the gas producer and power turbine are closely monitored and controlled by the engine FADEC via the gas producer governing system, which governs the gas producer speed, N_G, and the governing system which regulates the power turbine speed, N_P. The engine's acceleration schedule is adjusted according to information based on the N_G speed as well as ambient temperature and pressure. The atmospheric pressure is obtained via a transducer within the ECU. Fuel flow is provided to meet the required power demands. [10], [12]

The N_P governing system provides overspeed protection for the power turbine, governing its speed within the normal operating range. If loss of load occurs an analogue overspeed protection system comes into play once a certain overspeed percentage has been reached. [10], [12]

The temperature management system is made up of four thermocouples, chromel-alumel single junction types, which are positioned in the gas producer turbine outlet. The voltages acquired from these thermocouples are electrically averaged in a harness assembly attached to the motor before being forwarded to the ECU. Another temperature probe can be found inside the particle separator, this is known as the Compressor Inlet Temperature probe and it feeds atmospheric temperature information to the ECU so it may adjust the fuel schedule accordingly, decreasing fuel in order to decrease temperature. [10]

The power turbine output torque is provided to the FADEC system by a torque sensing port connected to a torqueometer oil pressure sensor. The FADEC responds to a torque limit exceedance by decreasing fuel flow. [10], [11]

In this way the FADEC of the C30 engine is able to fully control each of the engine's performance parameters via a network of sensors and actuators located throughout the engine.

Comments: *The similarities between the C30R/3 and T63 engine meant that the ECU for the C30 was considered as a possible starting point for incorporation into the T63 fuel system to replace the original mechanical ECU. This fuel control system was made for an engine with higher power specifications to those of the T63 and hence would have to be modified to cater for the new application. The system is available as a unit, machined from a single metal casting. System components are thus difficult to access, making modification thereof a complex task.*

2.2. T55- GA- 714A Engine Control System

The second system researched was that of the T55-GA-714A engine. The system provided an example of a commercially available ECU that employed an automated solution for both its primary and backup fuel control systems.

The T55 engine is used most notably in the Chinook helicopter and is the latest upgrade to the original T55 engine that was first created in the 1950's. This new upgrade introduces the use of a FADEC to control the engine and in particular the fuel system of the gas turbine. The fuel control system is designated the EMC-32T-2 made by Goodrich Engine Pump and Control Systems. [13]

The fuel metering system was built to replace the original hydro-mechanical engine control system and makes use of the original engine controls and sensors. Some of the duties which the FADEC performs are:

- Governing of the power turbine speed
- Torque smoothing using N_P rates
- Acceleration and deceleration control
- Engine temperature limiting
- Surge avoidance
- Compressor bleed band scheduling
- Fuel flow limiting and
- Engine failure detection

It achieves these tasks by means of the following systems:

Main actuators used are the “Primary” stepper motor and “Reversionary” stepper motor. The primary channel controls engine start-up by sequencing the fuel flow to the start and main nozzles as well as of the ignition sequence. [14]

During engine shutdown the primary system will close the metering valve to a minimum fuel feed position. The Reversionary system then kicks in and effects complete shutoff of the fuel at the operators command.

Engine temperature limiting is realised by reducing fuel flow if the temperature is slightly higher than acceptable levels and cutting off fuel flow completely if the temperature exceeds a given limit. If temperature during start up is excessive the starting sequence will be aborted. [14]

2.2.1. Hydro Mechanical Metering Assembly

The hydro-mechanical metering assembly of the T55 consists of a number of systems integrated together to gain control of the fuel flow to the combustor section of the engine. The following passages examine each of these systems individually, delving into the functions of each as well as how they affect the other systems.

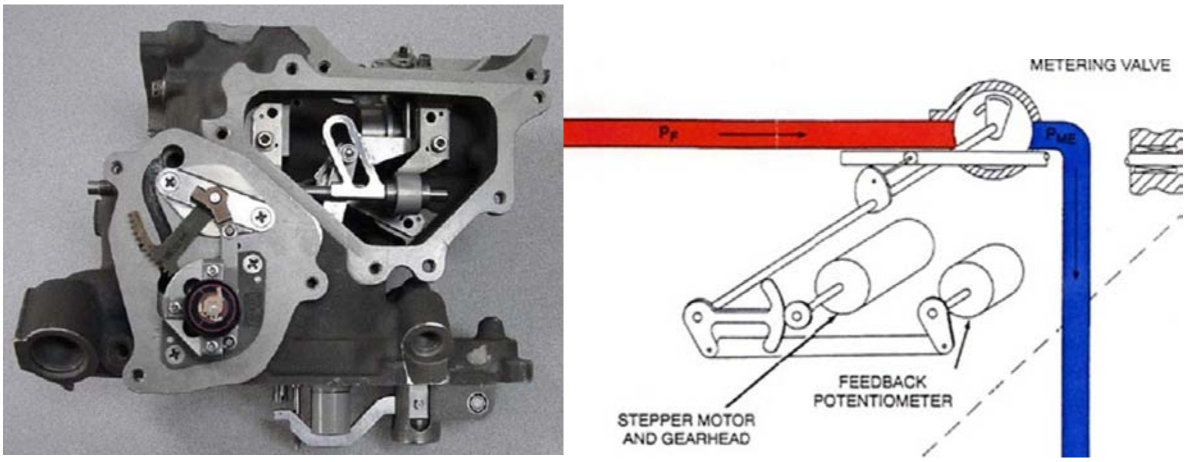


Figure 3: Primary stepper motor system
[15]

The primary stepper motor is capable of 500 steps per second with the full degree of movement being about 55°, this means that travel over the full range of movement is attained in one second. The feedback potentiometer incorporated into the system gives feedback to the **D**igital **E**lectronic **C**ontrol **U**nit (DECU) containing the metering valve position. [14]

The metering valve itself contains a spring-loaded wiper which rotates over an orifice in the metering valve plate. Primary mode allows control of the wiper via the primary stepper motor and DECU while in reversionary mode it is controlled via the Wf/P3 servomechanism. Inputs into this servomechanism move a linkage which controls the wiper. [14]

The metering head regulator keeps fuel pressure to the metering valve within the desired limits and bypasses excess fuel to the fuel pump inlet. If the Engine Control Lever is set to

STOP, all fuel will be passed back to the fuel pump inlet. These tasks are accomplished by means of the pressurising and shutoff valve. Another valve, the cam operated Windmill Bypass Valve, is operated by the revisionary motor. When this valve is activated it decreases the pressure of the fuel flow by dropping the control pressure of the metering head regulator. [14], [16]

The Reversionary system is a backup required for the case of primary system failure thus providing redundancy essential for a flight system. The Reversionary stepper motor shadows the operation of the primary stepper motor, that is connected to the PLA potentiometer and this provides the DECU with the motor position. [14]

A changeover solenoid facilitates the switch from Primary to Reversionary systems, when activated it disables the Wf/P3 servomechanism. When the solenoid is disabled it ports fuel pressure to the Wf/P3 servo and hydro mechanical speed sensor enabling Reversionary mode. The two systems are depicted in the schematic in Figure 4.

An N_G spool speed sensor is situated inside the Hydro Mechanical Unit. The signal from this sensor is fed back to the primary channel of the DECU allowing the DECU to prevent overspeed. Also within the HMU is a three phase alternator providing DC power to the FADEC system. This alternator provides a second, backup, N_G speed signal that is sent to both the primary and reversionary channels of the DECU. [14], [16]

A bleed solenoid valve is incorporated into the HMU as well; its purpose is to bleed the compressor system thus preventing engine surge. It is actuated by the DECU to either a fully open or fully closed position. [14]

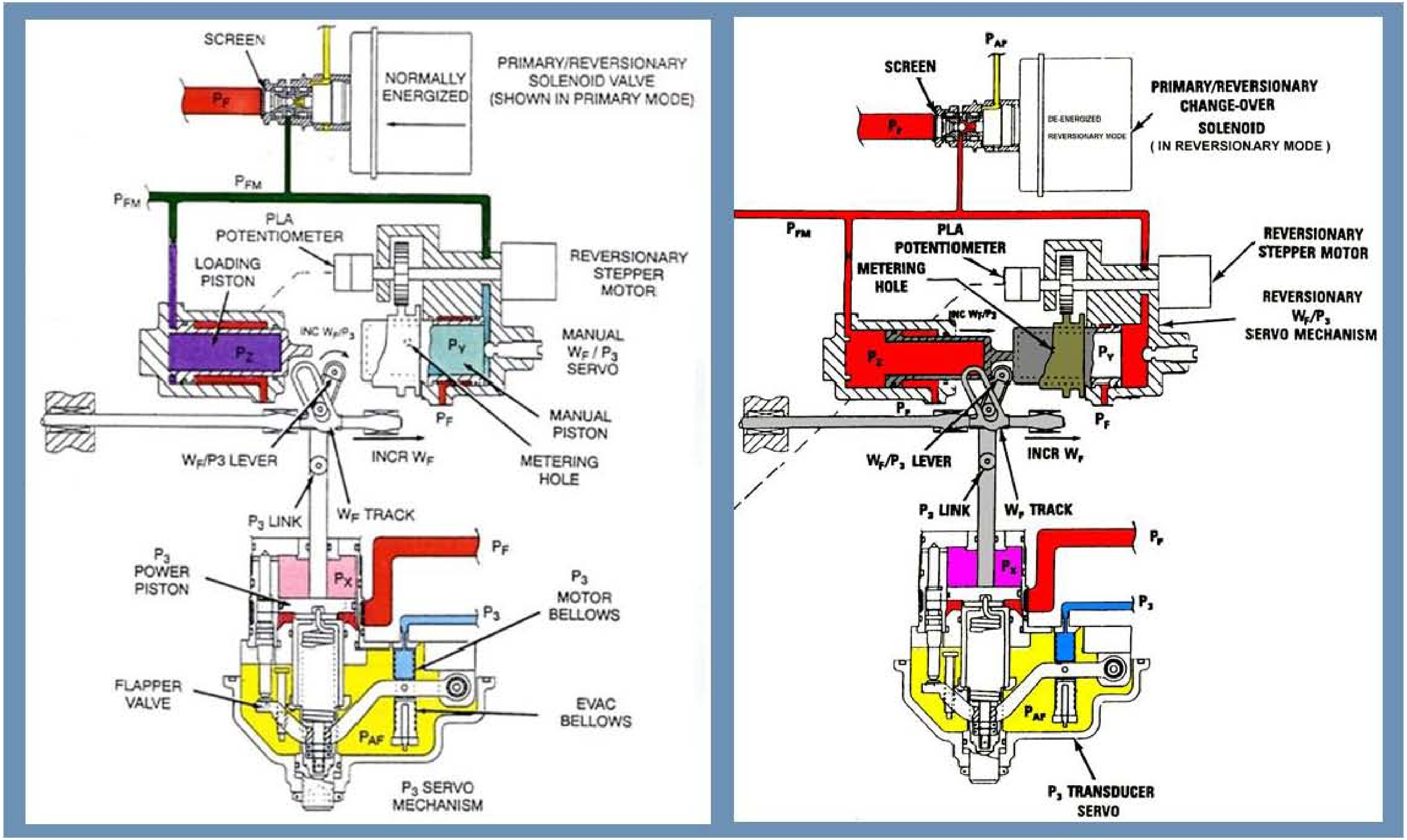


Figure 4: Primary and Reversionary system modes
[15]

2.2.2. Digital Electronic Control Unit (DECU)

The DECU is contained in a cast aluminium housing which protects against electromagnetic interference, radio frequency interference and electromagnetic pulses. There are primary and revisionary channels on the DECU that are used to control fuel flow to the engine. It also has sensors to detect atmospheric pressure and compressor discharge pressure (from the diffuser section of the engine). The unit stores information relating to the engine limits as well as any occurring faults and returns fault signals to the operator. [16]

Engine control levers are supplied that are connected to a friction brake which provides resistance when moving the levers. These levers allow the user to select positions that are sent to the DECU to initiate certain schedules. These schedules are as follows:

- STOP which shuts down the engine
- Ground takes the engine to ground idle speed and
- Flight which takes the engine up to 100% RPM

There are two switches for incrementing and decrementing the N_P spool speed allowing the user to fine tune the engine when it is in revisionary mode.

Furthermore a Thrust Control Position Transducer sends signals to the DECU that are relative to the load anticipation in Primary mode, thus allowing the controller to maintain the engine N_P speed by commanding the desired acceleration. [14]

Comments: *The fuel control system of the T55 makes use of two stepper motors which escalates system cost considerably. The backup motor must shadow the primary system to ensure correct positioning in the case of a primary system failure. The control system must therefore send positioning signals to both motors simultaneously, thus increasing the complexity of the control system. Two power sources must be supplied for the primary and reversionary systems to maintain system redundancy and provide a failsafe backup, resulting in an increased system cost.*

2.3. GE T700-701 Fuel System

The hybrid fuel system of the General Electric T700-701 was included in this review as it provides an example of an ECU implemented entirely through the use of electronic circuitry. The T700 turbo shaft and turboprop engine family was the most popular engine used to power intermediate size helicopters throughout the 1970's till the mid 1980's. The electronic control system was designed in the late 1980's to reduce pilot workload. A Hamilton Standard (now Hamilton Sundstrand) JFC-78 fuel control system was installed. The system incorporated automatic starting procedures, temperature, torque and speed limiting, torque matching and speed governing. Another improvement contributed by the control system was a notable decrease in fuel consumption during operations. The following segment of the literature review takes a closer look at this control system. [17]

2.3.1. Hydro-mechanical Unit

The hydro-mechanical unit of the T700-701C engine pumps, meters and pressurises the fuel to be used in the engine. Shut off of fuel to the engine is achieved through this unit. Another function the HMU performs is control of the gas generator speed; this is controlled via inputs from the ECU and the HMU torque motor allowing fine tuning to achieve turbine temperature limiting and speed. The HMU can deactivate the ECU in the case of ECU failure providing redundancy that is essential for safe operation of the engine. Figure 5 shows the layout of the HMU system. [7]

The torque motor servo located within the HMU is controlled via signals from the ECU. The main function of the torque motor servo is to trim the N_G output. Ground idle power is the minimum power limit while the upper limit is set by the Power Control Lever through a Power Available Spindle (the Power Available Spindle converts the linear to rotary inputs). The ECU of the T700 also performs turbine gas temperature limiting with the torque motor servo, overriding N_P governing and reducing fuel flow to the engine thus maintaining temperature limits. [18] [19]

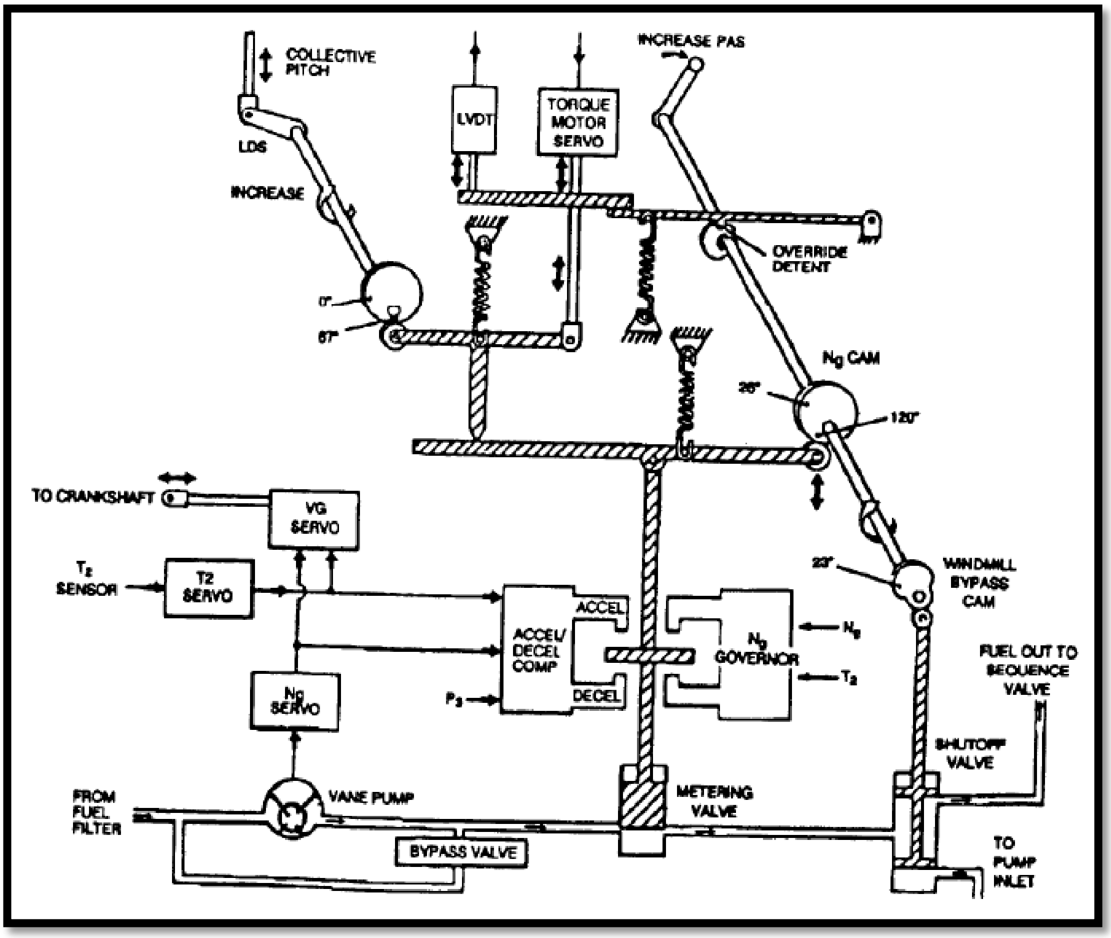


Figure 5: HMU schematic diagram
[7]

Part of the HMU is a high pressure fuel pump which passes fuel past the metering valve. The metering valve and a pressure regulating valve maintain the required engine fuel flow and bypass excess fuel to the pump inlet.

Another valve positioned within the HMU controls fuel flow between the main and primer manifolds and is known as the Overspeed and Drain valve. This valve can be used to shut off fuel flow completely as well as to provide N_P overspeed protection. Linear Variable Displacement Transducers are employed to give accurate feedback about positioning of the valve actuators. [7]

Overspeed protection for the Power Turbine (N_P) diverts fuel flow from the combustor leading to engine flameout, thus preventing N_P overspeed which can be very destructive. A solenoid valve is activated, opening a ball valve at the point when N_P reaches a set speed. The opening of this ball valve bleeds fuel pressure at the base of the selector valve. W4 is at high pressure causing the valve to shift downwards and bypass W4 back to the HMU inlet. The diversion of this W4 causes flameout. A schematic of the N_P overspeed protection system and of the ECU itself can be seen in Figure 6 and Figure 7 respectively. [7]

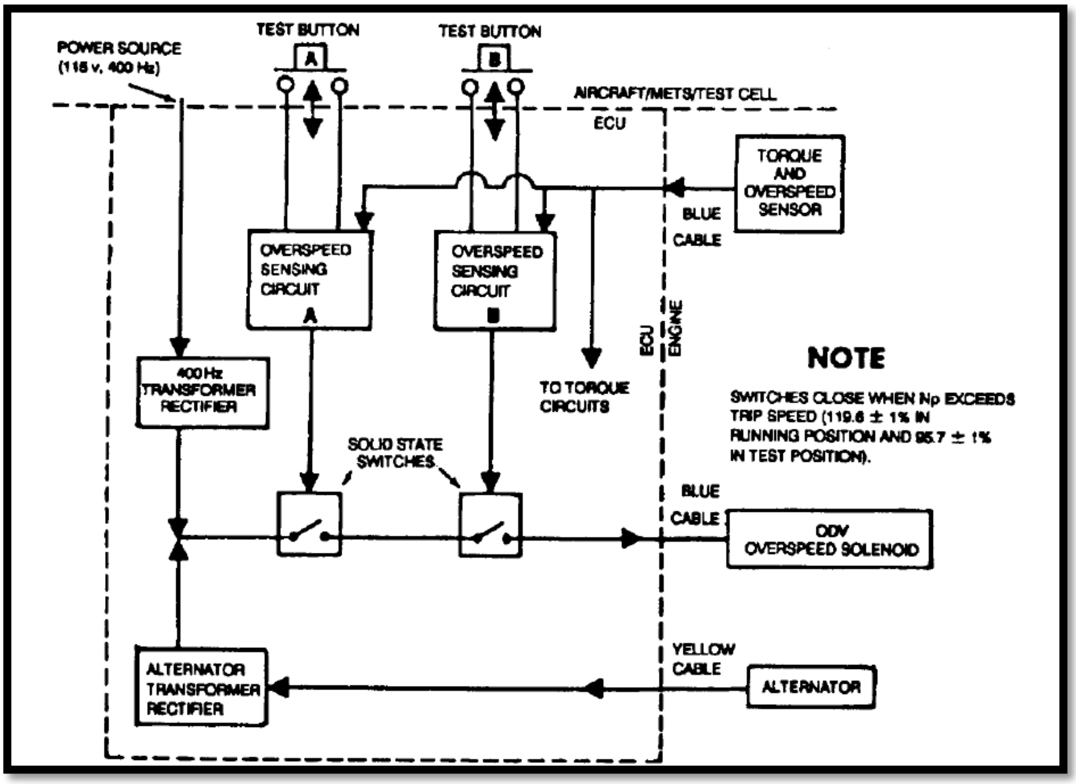


Figure 6: N_P overspeed protection system
[7]

Comment: *Electronic circuitry was used to implement the fuel control laws for the ECU implemented as the primary fuel controller for the T700 engine. This circuitry was built to the given specifications assuming given parameters. An alteration of these parameters, such as a change in fuel type used, would result in a need for new circuit boards to be designed and created. This reduces the flexibility of the system and inhibits future reconfiguration.*

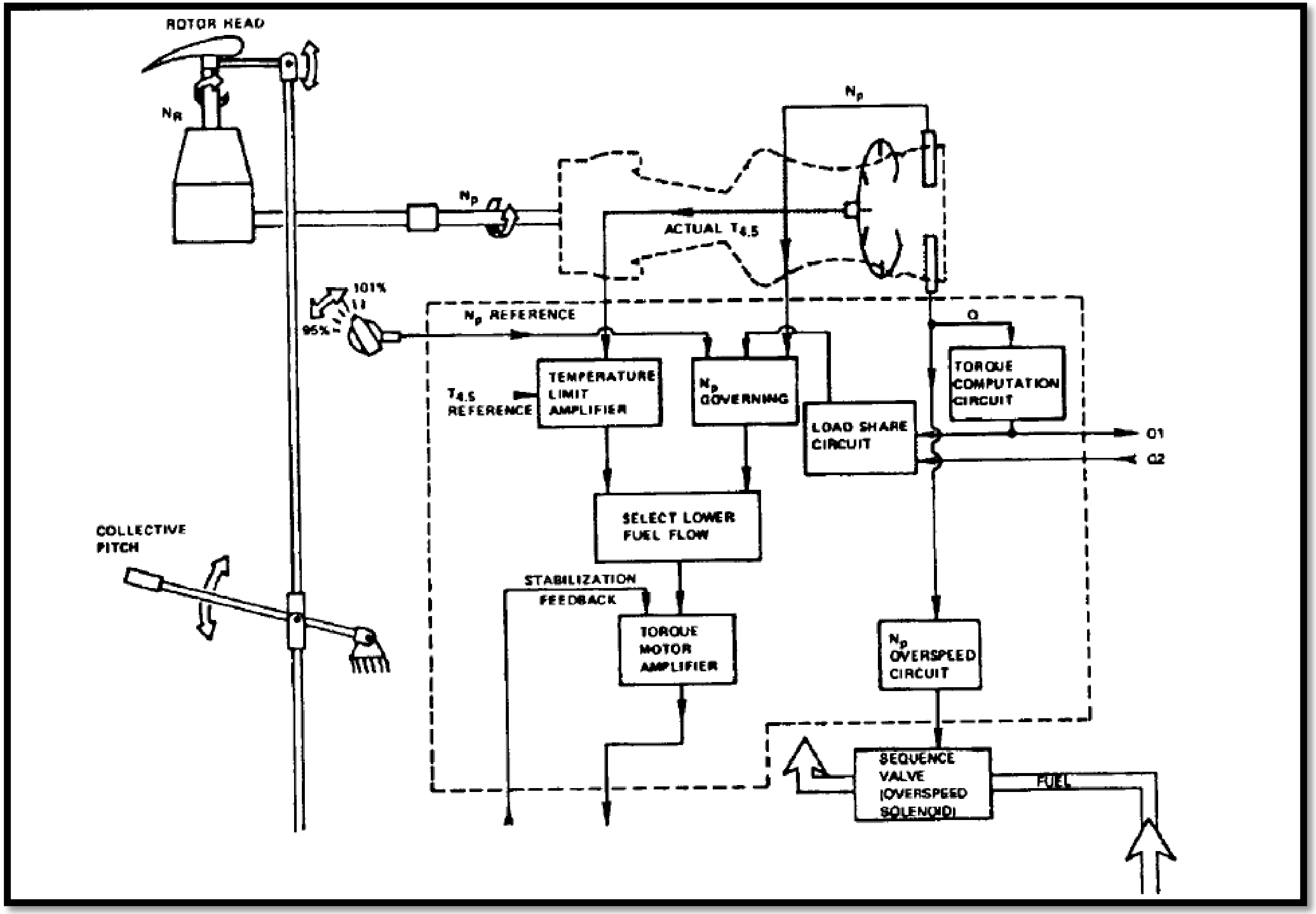


Figure 7: ECU schematic diagram
[7]

2.4. Allison Model 250-C20B Control System

Researchers at the Institute for Flight Propulsion at the Technical University of Munich created a digital control system for the Allison Model 250-C20B gas turbine. The controller was used as slave system for development, utilised in research projects such as those in which compressor instabilities were investigated at abnormal operating conditions. This system is included as an example of a laboratory implemented ECU that makes use of a software based controller.

The fuel system of the C20B comprised of a hydro-mechanical Bendix governor system much like that on the T63. The engine had been modified such that a digitally controlled fuel system ran in parallel with the original system. This second fuel flow control system was operated by a specifically designed FADEC. Each of the two fuel systems had its own high pressure fuel pump supplied with fuel from a single source as is illustrated in Figure 8.

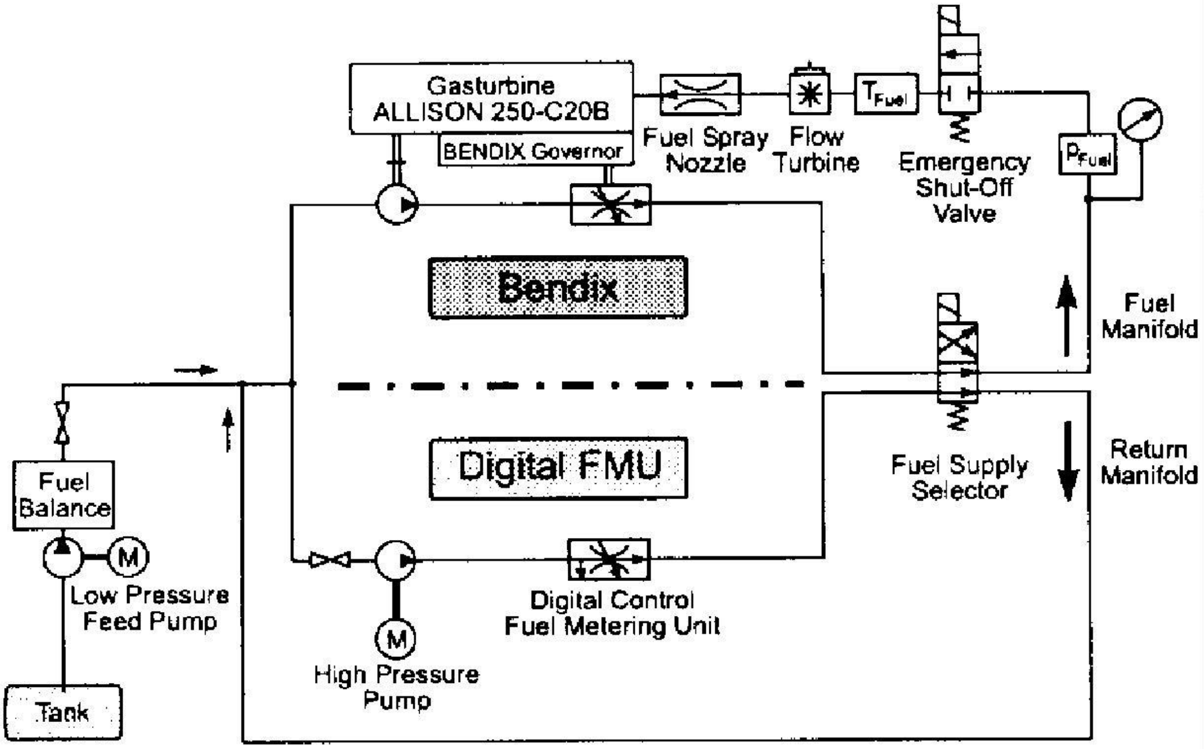


Figure 8: Schematic of modified fuel flow system on C20B [20]

A safe transition between the two fuel control systems could be executed when the engine was in idle mode as well as from digital to mechanical at any point in operation. This feature allowed the mechanical system to function as a backup in the event of malfunction in FADEC operation. The test cell operator could also request fuel control system changeover.

The digital control system had been set up to account for both component wear and fuel consumption. Researchers involved with the development of the digital control system found that sufficient bandwidth of the fuel controller was to be had with the clock control set to 60Hz.

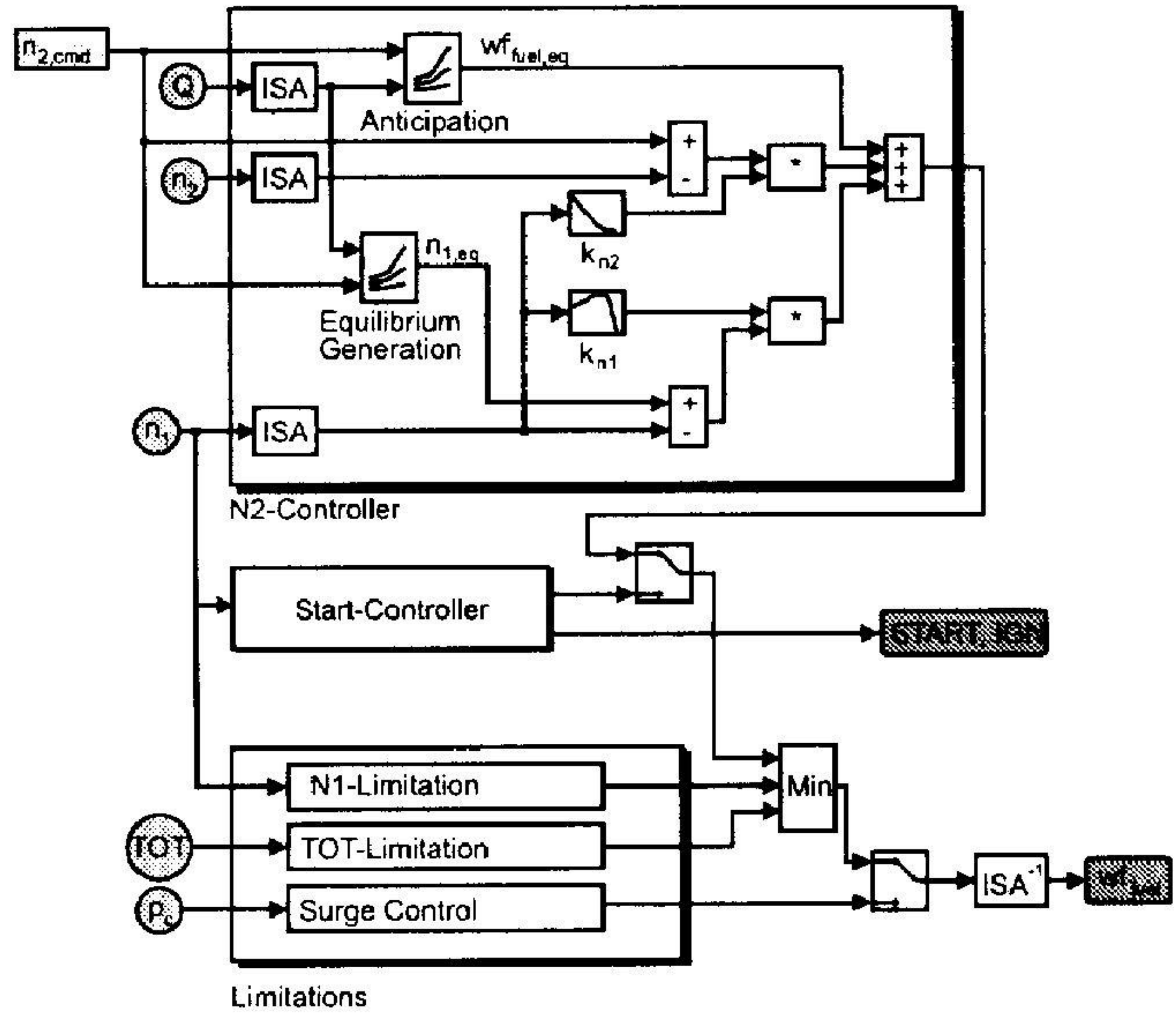


Figure 9: Engine control schematic of FADEC developed for C20B [20]

The FADEC system developed for use on the university's C20B executed a variety of control laws that performed the following functions on command:

- Start up and stabilisation in idle mode utilising the starter motor, igniter and fuel flow controller
- Maintained N_P speed at a pre-set value for a given torque by maintaining required N_G speed via a calculated fuel flow
- Regulated N_P speed given a constant fuel flow rate through adjustments to the load torque of the eddy current dynamometer.
- Maintained a pre-set N_P speed with a given torque by adjusting the fuel flow and air bleed from the compressor

Certain operating parameters such as N_G speed and TOT of the engine were limited throughout all operational modes to ensure functional integrity of the engine structure. Figure 9 shows the engine control layout for the FADEC.

Original development code for the control software of the FADEC was written in C and Assembly [21]. Matrix Laboratory (MATLAB) and the SIMULINK graphic development environment were used to design and test the more recent version of the FADEC. The finished product was then automatically compiled into C before being deployed to the target hardware. The hardware used consisted of a dSPACE multiprocessor and a Texas Instruments TMS320C40 digital signal processor. The user communicated desired parameter changes and commands to the FADEC via a **G**raphic **U**ser **I**nterface (GUI). [20], [22]

The compressor bleed valve of the C20B was replaced by another designed and manufactured at the university. The new bleed valve was electronically actuated by an RC servo motor under control of the FADEC system. Incorporation of the new bleed valve into the system led to enhanced engine operation and gave better control of compressor stability.

Software was also created that utilised wavelet methods to detect engine surge conditions. Initial experimentation proved promising however actuator dynamics were inadequate to avoid surge completely.

Future considerations for the controller were to involve investigations into fuzzy and adaptive control strategies.

Comment: B*oth the hardware and software layouts used in the design of this control system provide a good example of possible system application for the T63. The automated compressor bleed valve provided an additional level of control and improved compressor stability and should be kept in mind as a possible future improvement to the T63 system.*

An investigation into the controllers of four aero gas turbines has been performed so as to provide an insight into the pros and cons of previously implemented designs. The ECU's of similar systems, such as that of the C30R/3 were explored as possible options for application as replacements of the HMU of the T63. A summation of knowledge acquired whilst reviewing the four chosen electronic control systems yields the following points. These were to be taken into consideration during design of the ECU for the T63 engine:

- Modification of an existing ECU would be likely to prove to be a difficult task due to the tight physical constrains of the systems. These units also come with a high price tag that may significantly strain the given budget.
- A redundant fuel control system should be incorporated into the system design to offer a backup in the event of system failure.
- Two electronically actuated control systems would increase the cost of the system due to the requirement for two actuators and separate power supply systems. A hybrid design merging a mechanical and electronically controlled fuel system is therefore preferable.

- Employing two electronic fuel control systems to provide redundancy increases complexity of the control system as control signals must be sent to both systems simultaneously. The control system must therefore send positioning signals to both motors simultaneously, thus increasing the complexity of the control system.
- A controller implemented purely through electronic circuitry inhibits future reconfiguration of the system, requiring a rebuild of the controller to allow changes to be made to the control system.
- A software based controller (as opposed to circuit based) provides greater flexibility and options for future reconfiguration.
- The compressor bleed valve of the T63 could be automated to offer improved control and compressor stability.

2.5. Control & Software

Helicopter gas turbines have been designed to obtain maximum power with a minimum engine weight, this has inevitably led to the requirement for the engine to operate nigh on or at their mechanical, thermal and pressure limitations. Feedback control has therefore been an essential aspect to ensure that the engines operate within safe boundaries. The controller must both regulate and limit the main fuel control so desired power may be provided while ensuring that limit protection is enforced via the acceleration and deceleration schedules. [1]

Initially all implemented controllers were of the hydro mechanical type, employing cams and mechanical integrators to enforce simple control strategies. Moreover these robust, failsafe devices are used in current gas turbines, providing backup systems for the latest generation of control systems. With an ever increasing demand for improved performance and greater fuel efficiency electronic controllers began to be implemented from the 1980's. These controllers rely on sensors and actuators to give greater functionality through the use of higher loop gain and more complex strategies and algorithms. [1]

The larger portion of present day gas turbine engines operate under the control of SISO systems. These systems usually use the fuel metering valves to regulate fan speeds or pressure ratios much in the same way as the HMU's operate but under far more accurate control thus giving a wider operational range. Relatively simple SISO control laws were designed via pole placement techniques grounded in linear control theory and achieved in two steps. First a local linear controller was designed according to a simplified linearization of the gas turbine at a number of operating points. The gains of these local operating points would then be interpolated to acquire a global non-linear controller. This method of fashioning controllers is well practiced and popular but cannot ensure stability, robustness and performance on a global level and hence extensive simulations must be performed to guarantee these characteristics [2], [3]. The first electronic controllers of this type were analogue systems however these were superseded by the digital FADEC systems of today. [2]

2.5.1. Sensors

Several sensors are to be found in most gas turbines, of these the N_G and N_P speed sensors are used to determine when overspeed limits are approached. Thermocouples monitor inlet and outlet temperatures of the turbine. However their need to be shielded results in these sensors having a slow response time rendering them less ideal for control purposes. The most common sensors used for control of the engine are the pressure sensors. Engine manufacturers use either the **E**ngine **P**ressure **R**atio (EPR) or more commonly: the fuel flow divided by compressor exit pressure (W_f/P_3). EPR is equal to turbine outlet pressure divided by compressor inlet pressure. W_f/P_3 is directly linked to both the flame and turbine temperatures via the air fuel ratio and is therefore W_f/P_3 can be used to control the turbine temperature and prevent blowout and stall. [1]

Temperature, pressure, speed and torque at various stages within a gas turbine are monitored by means of numerous sensors located throughout the engine and helicopter or test cell and fed into the control unit.

- Electromagnetic pick-ups relay rotational spool speed
- Thermocouples measure temperatures in various locations
- Pressure transducers for the required pressure readings
- Engine torque is also detected by various means such as a strain gauge based transducer or magnetoelastic torque sensor.

Critical sensors providing feedback from components that require careful monitoring often have redundancy to minimise the probability of malfunction.

In engines with only hydro mechanical controllers, the simplest form of control was provided by controlling the gas generator or core speed of the engine. This produced the desired output while keeping the engine within the operating range. Digital controllers are used to regulate fan speed (in the case of turbofan engines) or pressure ratio to gain more accurate control of power. A closer look at this method of control follows. [1]

2.5.2. Core Speed Control

Control schedules for core speed are created for both steady state and transient engine operation. Given an inlet temperature and throttle position these schedules are designed to deliver the desired core speed. Within the controller, gain is determined as a function of core speed so control may be maintained over the full operating range of the engine and the change in fuel flow determines how the metering valve is positioned. This provides an effective control response for changes in throttle angle. The gain value is made high to decrease the increase in speed error with increasing load if a proportional controller is employed. If an integral controller is used, the set point tracking characteristics of the controller are greatly improved and a zero error margin is possible. An example of a control set up for core speed control can be seen in Figure 10. [1]

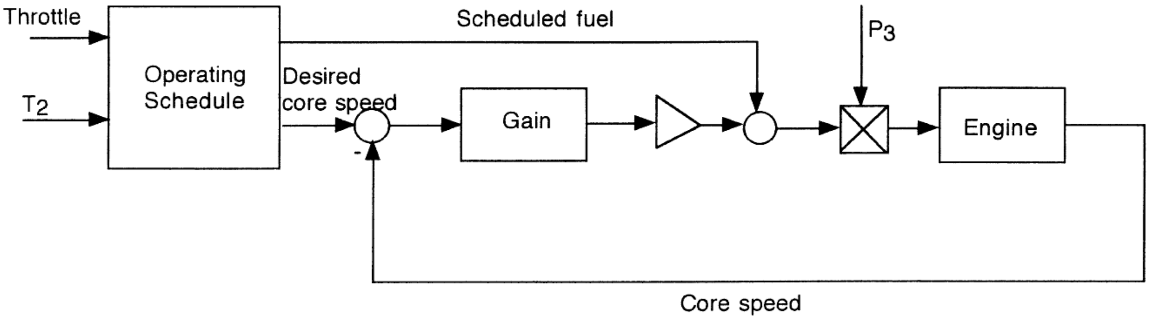


Figure 10: Typical core speed control set up [1]

A transient control schedule is required to facilitate acceleration and deceleration of the engine as well as to ensure that stall, flameout, and temperature limits are adhered to. Controllers are designed to run the engine as close to its limits as possible without breaching them as this allows for faster acceleration and deceleration as well as greater efficiency. The deceleration limits are set so that a minimum fuel flow rate prevents flameout. A proportional idle speed control is also incorporated to retain the engine at a minimum operating speed. The block diagram in Figure 11 shows the typical layout of a controller with both steady state and transient control conditions incorporated. [1]

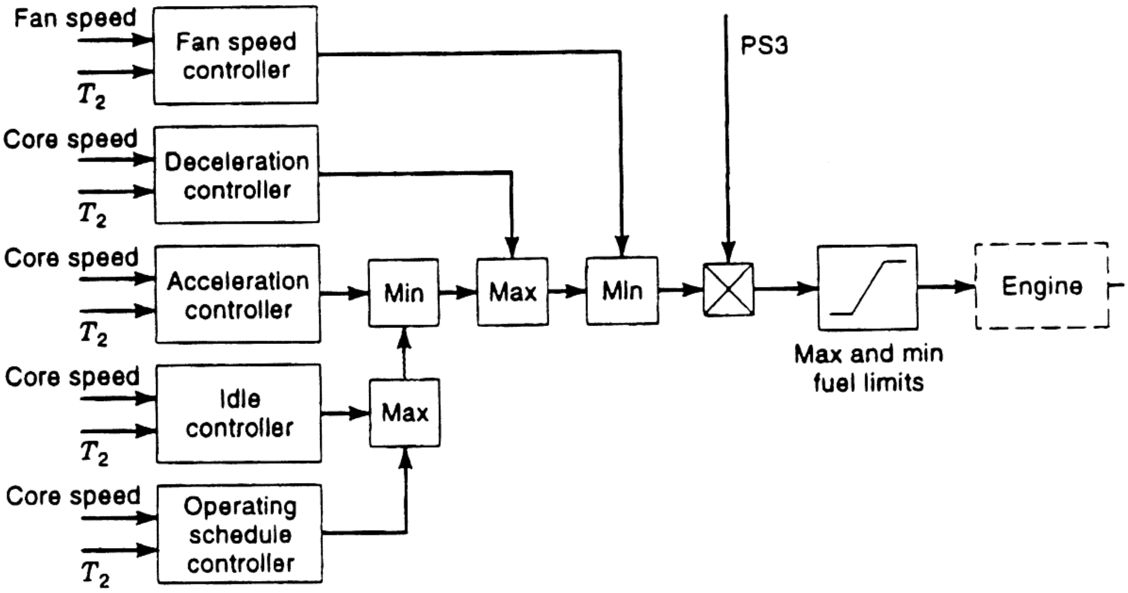


Figure 11: Complete controller layout [1]

2.5.3. Formulation of a Control Law

Future work on the T63 fuelling system was to entail the formulation of a control law for the gas turbine. This design process requires a model of the system used to simulate engine behaviour and as a foundation on which the design of the control system may be based. This model can either be of mathematic origin (often defined via thermodynamic principles in the case of gas turbines) or alternatively a system identification procedure could be carried out to obtain a model that approximates the dynamic behaviour of the system. In some cases both models will be used to provide validation [23], [24].

The methodology most often put to practice when dealing with aero-derivative gas turbines is that of employing a gain-scheduling controller designed using a model of the engine linearised at a number of operating points [25]. These partially linearised models may be obtained via either of the aforementioned means. A popular method of the application of system identification to obtain an engine model is the use of frequency domain identification

[23]. This method makes use of inputs applied at varied frequencies to elicit system responses which can be used to describe the system's linear dynamics. In the case of non-linear systems these responses give a linear approximation of system behaviour. [26]

2.5.4. Control Parameters

The strategy used in control of turboshaft engines is to consider the output shaft and power turbine combination as a load imposed on the gas generating system. Disturbances emanate from changes in load on the gas generator loop caused by increased demand for power or, in the case of engines fitted to an aircraft, gusts of wind.

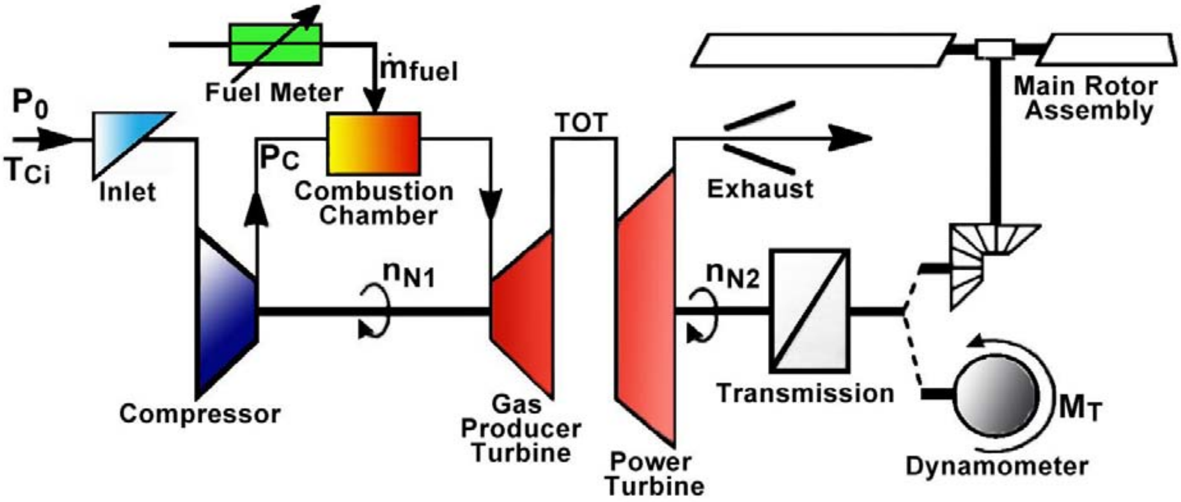


Figure 12: Schematic layout of gas turbine input & output parameters (Modified from [21])

An engine must always operate in a safe and reliable manner throughout all modes of operation. This requires that all mechanical, thermal and aerodynamic limits be maintained and upheld by the control system. Certain variables (some of which are shown in Figure 12) need to be carefully monitored and controlled to ensure proper functioning of the gas turbine while achieving peak operating efficiency. Variables that must be strictly kept within the specified limits are the:

- Outlet gas temperature from the turbine (TOT) is an indicator of the more critical turbine inlet temperatures, as such it should be carefully monitored and controlled to prevent thermal damage to the turbine blades and exhaust ducts
- Compressor surge margin via acceleration control, thus preventing unstable operation
- Power turbine speed must be maintained at a relatively constant value
- Gas producer spool speed must be held within the specified operating limits and
- Torque must be held below a maximum value

Control of these variables is exerted through manipulation of the fuel flow rate as well as through bleed valves situated around the compressor.

Engine manufacturers specify maximum values for inaccuracy at steady state (typically 1%) [27]. The required response time of the control system should be founded on guidelines stated by the **F**ederal **A**viation **A**dministration (FAA) and **E**uropean **A**viation **S**afety **A**gency (EASA).

Section CS-E 745 of the EASA Engine Specifications [28]on engine acceleration states that the following should be demonstrated on a test bed:

- The engines of rotorcraft must be capable of acceleration from “minimum test bed idle to rated Take-off in not more than one second with the appropriate adverse combination of bleed air and power extraction to be permitted in the aircraft, without over-temperature, surge, stall or other detrimental factors occurring to the engine.”
- It must also be possible in all aero engines for an increase to be made “from 15% of rated take-off power or thrust, to 95% of the rate take-off power or thrust in a time not greater than 5 seconds.”

These specifications correspond with those issued by the FAA, found in Section 33.73 [29] of the Aircraft Certification Handbook describing power and thrust response:

“The design and construction of the engine must enable an increase--

- From minimum to rated takeoff power or thrust with the maximum bleed air and power extraction to be permitted in an aircraft, without over temperature, surge, stall, or other detrimental factors occurring to the engine whenever the power control lever is moved from the minimum to the maximum position in not more than 1 second, except that the Administrator may allow additional time increments for different regimes of control operation requiring control scheduling; and
- From the fixed minimum flight idle power lever position when provided, if not provided, from not more than 15 percent of the rated takeoff power or thrust available to 95 percent rated takeoff power or thrust in not over 5 seconds. The 5-second power or thrust response must occur from a stabilized static condition using only the bleed air and accessories loads necessary to run the engine. This takeoff rating is specified by the applicant and need not include thrust augmentation.”

Processor and communications speeds are regulated by the requirement for a safety reaction time that should execute within milliseconds. While other time constraints, such as the update rate of a display panel, are based on the bounds of human perception.

2.5.5. Sampling Rate

A digitally controlled system offers flexibility and re-configurability however there are a number of factors that should be taken into account. A trade off must be made between cost and performance when deciding on an appropriate sampling time. Longer sample intervals allow more computation time for processing of signals. Despite an increased cost and performance requirement associated with a shorter span the data relayed better reflects the original signal.

Controllers need to be designed to give adequate system stability during various modes of operation as well as when faced with a number of disturbances. Both stability and performance of a system need to be robust with respect to system uncertainties and disturbance signals. Disturbance signals and measurement noise should be attenuated to a suitable degree and adequate tracking attained to ensure the robust nature of the control system.

The objective when designing a control law for a system is for the system output to attain tracking of a given input reference as closely as possible. The faster the sampling time and the closer the approximation to the original signal the less the likelihood of an erroneous reading.

The Nyquist Sampling Theorem prescribes a nominal sampling rate of at least double the highest frequency component of a time-varying input signal.

$$f_{sampled} \geq 2f_{input} \tag{i}$$

If the phase of the signal being sampled is known then it is possible to sample at the Nyquist rate. For all other cases the rule of thumb maintained in industry is that this sampling rate should be considerably higher than the bandwidth of the signal being sampled [30] [31]. The sampling rate should also be greater than the highest frequency of any disturbances that might affect the input signal.

The sampling time of a control system must be relatively short in relation to the time constant that dominates the transient response of the system or there may be distortion of the signal in the form of aliasing. Aliasing is the effect that is seen when a high frequency signal is sampled at low frequency. As a result this high frequency component appears as one of a lower frequency and cannot be distinguished from the system's lower frequency response. An example of aliasing is shown in Figure 13. The input signal pictured in blue is sampled (green) at 8 Hz a frequency lower than that of the signal itself. This leads to the signal being read in as a lower frequency signal (red).

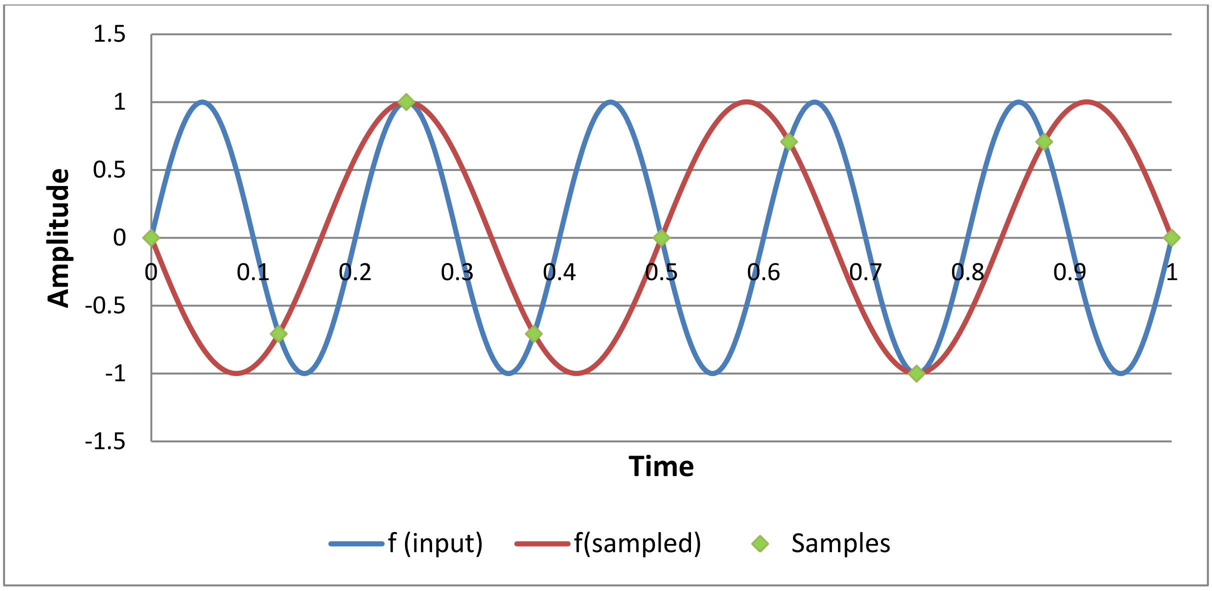


Figure 13: Effect of aliasing

2.5.6. System Excitation for Identification

The section that follows forms a foundation understanding of system requirements necessary to be developed as a base to enable the future Phase II of the project. The future development of a fuel control law for the gas turbine requires that the dynamics of the engine and actuators be modelled. These models are then used to simulate the device's response to a given input allowing analysis of transients and forming the basis for the design of the control system. The engine models are obtained either from highly complex performance based models or estimated from experimental data. [32]

Signals commonly used when performing system identification include: impulse, step, ramp, parabolic or sine-wave testing. Typical methods employed in the design of fuel controllers for gas turbine engines involve engine excitation via step or sine-wave testing over a number of frequencies either in the form of single-, chirp or multi-sine tests.

Step testing is the method most often employed in analysis of systems and the resulting step response can be evaluated to give information about a dynamic system's transient response and stability. System characteristics such as overshoot, rise and settling time can also be determined.

Single Sine testing requires an extensive time allocation, thus focus is shifting towards chirp or multi-sine testing. Sending a chirp as an input signal involves the transmission of a sinusoidal signal whose frequency increases or decreases over time, allowing a range of frequencies to be tested over a given time period. Multi-sine signals are deterministic, periodic signals comprised from the sum of harmonically related cosines, represented by:

$$u(t) = \sum_{k=1}^{N} A(k)\cos\left(i(k)\omega_0 t + \emptyset(k)\right) \tag{ii}$$

Where N was the number of test frequencies in the signal, A represents amplitude, i the harmonic numbers, ω_0 the fundamental frequency and $\emptyset$ the phase at each test frequency. The graph in Figure 14 shows an example of a multisine signal.

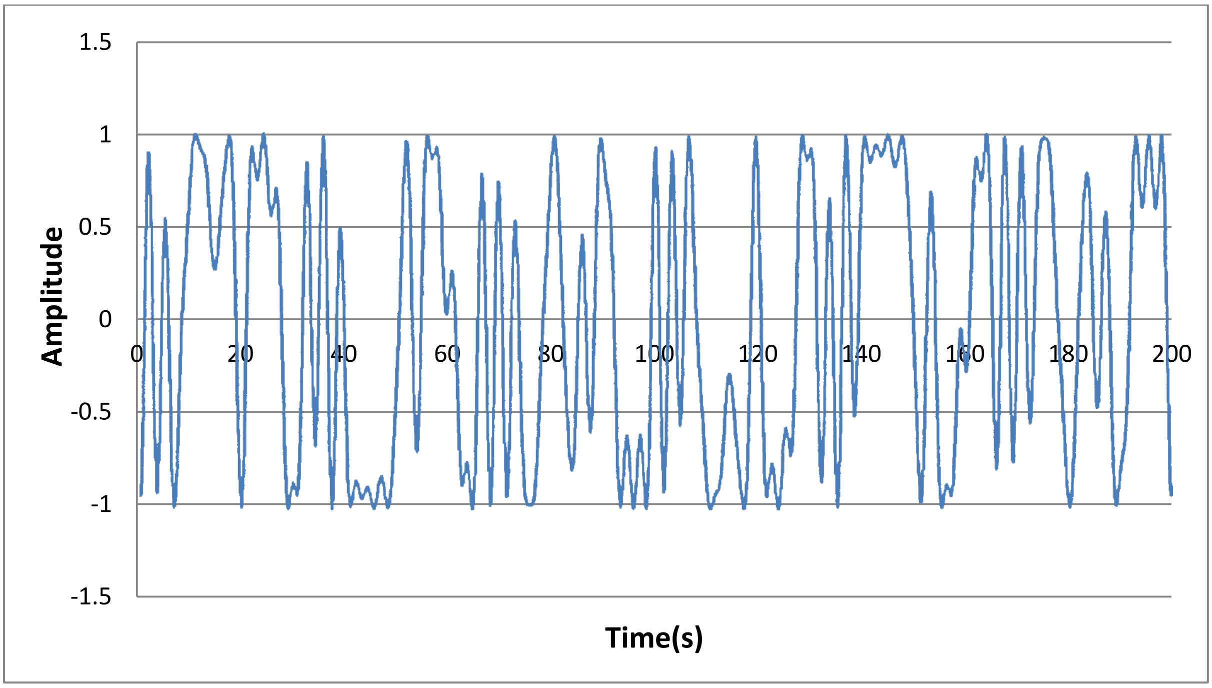


Figure 14: An example of a multisine signal

The crest factor expresses the dynamic range for the input signal given as a measure of the peak amplitude of the input signal divided by the root mean square (RMS) value.

$$CF = \frac{|u(t)|_{peak}}{u(t)_{rms}} \tag{iii}$$

Reduction of this crest factor results in the maximum power input for a given amplitude, minimising nonlinear distortions and shortening measurement times. [33] [34]

The data obtained may then be used to estimate the parametric and non-parametric models in the frequency domain. The sinusoidal plots and the systems frequency response may also be used to determine system characteristics such as stability and steady state error.

The frequency response of a system is the relationship between the magnitudes and phases of the steady state input and output signals. The input signal must take the shape of a sinusoidal waveform with a constant amplitude and variable frequency. The output signal will then also take the form of a sinusoid however its magnitude and phase are determined by the characteristics of the system.

If a sinusoidal input of amplitude A_0 and frequency ω given by:

$$u(t) = A_0 \sin(\omega t) \tag{iv}$$

is used to excite a system $G(s)$. At steady state the output signal with amplitude $A_0|G(j\omega)|$ will be:

$$y_{ss}(t) = A_0|G(j\omega)|sin\,(\omega t + \varphi(\omega)) \tag{v}$$

Taking the Laplace transforms a transfer function can be fashioned from this data taking the form:

$$Y(s) = G(s)\,U(s) \tag{vi}$$

Then:

$$G(s) = \frac{Y(s)}{U(s)} \tag{vii}$$

The system's frequency response is given by $G(s)$evaluated at $s = j\omega$, giving:

$$G(j\omega) = |G(j\omega)|e^{j\varphi} \tag{viii}$$

Where $|G(j\omega)|$ is the magnitude and φ is the phase, their respective forms given by:

$$|G(j\omega)| = \sqrt{\{Re[G\,j(\,\omega)]\}^2 + \{Im[G\,j(\,\omega)]\}^2} \tag{ix}$$

$$\varphi(\omega) = \tan^{-1}(\frac{Im[G(j\omega)]}{Re[G(j\omega)]}) \tag{x}$$

From these equations Nyquist, Bode or Nichols plots may be drawn to analyse system stability and predict transient and steady-state performance in the time domain.

Using the system excitation method mentioned above one can proceed with system identification. This can be done by regression for linear model parameters using the points from the experimentally determined bode plot. Another method to obtain a linear model is via system identification using a tool such as that offered by the Maths Laboratory (MATLAB) system identification (SYSID) toolbox. Transfer functions for the conditions that are to be controlled can then be synthesised. Which takes the form of:

$$H(s) = \frac{Y(s)}{X(s)} \tag{xi}$$

These transfer functions are the linear mappings of the Laplace transform of the input $[X(s)]$, in this case the fuel flow rate, to the Laplace transform of the outputs $[Y(s)]$ – temperature, gas producer speed and power turbine speed. Linearised models of each of these conditions can then be constructed around a number of set operating points over the stable range of gas turbine operation to determine the relevant control laws.

The aforementioned control theory covered in this chapter serves to lay down guide lines for specification and design of the electronic control unit to be created as a part of this thesis. These guidelines ensure that the ECU developed will be capable of facilitating the future work that has been scheduled to be carried out using the T63 gas turbine. Chapter 3 describes the formulation of two engine models constructed to give clear objectives for the requirements of the control system that was to be guided by the knowledge gained over the course of the literature survey.

LITERATURE REVIEW

3. Modelling the Fuel Effects

The objective of this project was to create an engine controller that allowed freely adjustable scheduling of fuel to the engine. The end goal was to enable full characterisation of the fuels and their effects on the engine. Particular attention was to be paid to the lean blow out point of the engine when operating on each fuel. This chapter contains the theory behind the model constructed to investigate this behaviour as well as data generated using this model.

3.1. The Models

Idealised Gas Cycle

Two fuel blends were employed within the theoretical model to simulate the compression, combustion and expansion processes and effects thereof within the gas turbine. During this process a mixture of fuel and air are entrained into the combustion chamber of the gas turbine. The hydrogen and carbon molecules of which the fuel is composed react with the oxidiser to form CO_2 and H_2O in directly proportional quantities to those of the original hydrocarbon molecule.

The T63 gas turbine has been used to test two fuels in particular, these being petroleum derived Jet-A1 and Synthetic Paraffinic Kerosene (SPK). Two model fuels with widely known chemical characteristics were utilised to simulate Jet-A1 and SPK. A blend of both aromatic and paraffinic fuels was adopted to give the equivalent hydrocarbon molecule that best represented each fuel. Jet-A1 was simulated using a blend of Toluene and n-Heptane in percentages of 25.70% and 74.30% respectively. SPK on the other hand was blended from a 7.78% Toluene and 92.22% n-Heptane mixture. The hydrogen mass content calculated using these blends works out to 13.42% for Jet-A1 and 15.17% for SPK thus correlating with the ASTM Fuel Specification Test Results in which Jet-A1 is listed as having a minimum hydrogen mass content of 13.4% while 100% SPK is stated as 15.3%. This contrasting hydrocarbon (H/C) ratio of the two fuels affects changes in the reaction chemistry as well as the specific energy and heats. This in turn influences the properties of the combustion products. The specific heats of a fuel with a higher H/C ratio are lower as more H_2O is formed. H_2O has a lower specific heat than CO_2 thus the specific heat value obtained at constant pressure (C_p) would also be lower. The specific heat at constant volume (C_v) may be calculated using:

$$C_v = C_p - R \quad \textbf{(xii)}$$

Where R (kJ/kg.K) represents the specific gas constant obtained via division of the universal gas constant (R_u) (kg/kmol.K) by the specific molar mass (M) (kg/kmol) of the species involved in the reaction:

$$R = \frac{R_u}{M} \quad \textbf{(xiii)}$$

The ratio of specific heats is given by:

$$\gamma = \frac{C_p}{C_v} \qquad \textbf{(xiv)}$$

This ratio may then be utilised to determine the idealised, isentropic, specific work done by the compressor, thus accounting for the characteristic changes of the gas when compressed:

$$\omega_{comp} = \frac{\gamma}{\gamma - 1} R(T_2 - T_1) \qquad \textbf{(xv)}$$

Where $T_1$and T_2 are the inlet and outlet temperature of the compressor respectively. Thus a higher H/C ratio would result in an increased specific gas constant and specific heat ratio of components entering the combustion chamber.

When comparing Jet-A1 and SPK at the same output power it is assumed that inlet conditions are equivalent with an inlet temperature of 27°C and air entering the compressor at one atmosphere of pressure. Compressor efficiency in both cases will also match. For the purposes of this model the compression and expansion processes were taken as being isentropic. The gas producer turbine shares a shaft with the compressor, thus work carried out by the turbine must equal that required to compress the air. Given a constant power output by both the gas producer and power turbines it can therefore be deduced that the compressor exit temperatures and pressures as well as the mass flow rate of air are also equal in each instance. It can also be assumed that throughout the process the mass flow rate of air from the compressor will be constant as is the inlet temperature of the combustor.

The inlet pressure of the combustor was taken as five atmospheres absolute. Combustion efficiency was assumed to be 100% with no pressure loss. Using the aforementioned fuel blends and assuming adiabatic combustion the final temperature of combustion can be calculated. The model does not account for transition reactions, instead the initial reactant mixture and final products are assessed to give the total change in enthalpy and heat of energy released. The Chemkin® thermodynamic parameter database was referenced to obtain the values of enthalpy and entropy for the combustion components. Two dissociation reactions are incorporated into the model, these being for CO_2 and the Water–gas shift. The inclusion of these reactions provides a more accurate portrayal of the total heat released and final temperatures of combustion. Nitrogen that enters the equation as a component of the air drawn into the engine via the compressor is regarded as an additional inert gas component. This component passes through without participating in the reactions to form mono-nitrogen oxides. Two separate models were employed to determine the adiabatic flame temperature (AFT) associated with each fuel. Given the reactant temperature this AFT was then used to calculate the specific gas temperature and properties. For a given equivalence ratio when using Jet-A1 fuel and the power output of the power turbine, the model was constructed so as to give the fuel flow rate associated with the SPK fuel to achieve the same power value.

Well-Stirred Reactor

A controller was to be created for the T63 with the ultimate aim being to allow “off-map” fuel scheduling and in particular to investigate the blow out limits and effects on the engine. It was therefore desirable to create a theoretical model of blow out to determine the expected flammability limits. To achieve this the combustion chamber of the T63 gas turbine can be modelled as a well stirred reactor such as that depicted in Figure 15 and described in Lefebvre's "Gas Turbine Combustion" [35].

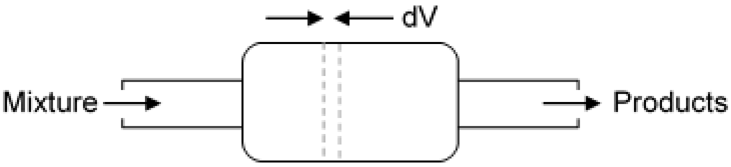


Figure 15: The well-stirred reactor

The fuel supplied to the engine may be defined by:

$$Fuel\ Supply = \Phi.x_s\dot{\text{N}} \qquad \textbf{(xvi)}$$

Where ϕ is the molar fuel/air equivalence ratio, x_s is the stoichiometric fuel mol fraction and $\dot{\text{N}}$ is the mixture flow rate in mols/sec.

Fuel is consumed at a rate $\frac{d}{dt}[F].dV$ across the volume element dV, where the fuel concentration, $[F]$, is number of mols (fuel) per total volume. As per Strehlow's "Fundamentals of Combustion" [36] the chemical change in the reactor can then be given by:

$$\frac{d}{dt}[F].dV = \Phi.x_s\dot{\text{N}}.dy_F \qquad \textbf{(xvii)}$$

This may be integrated over the full reactor volume and the fuel consumption profile resulting in:

$$\frac{V}{\Phi.x_s\dot{\text{N}}} = \frac{Y_F}{\frac{d}{dt}[F]} \qquad \textbf{(xviii)}$$

Where Y_F is the consumed fuel fraction and $\frac{d}{dt}[F]$ is constant for a reactor with homogenous fuel content. The rate of reaction is assumed to have a general order in both fuel and oxidizer concentration and an Arrhenius temperature dependence which can be expressed as:

$$\frac{d}{dt}[F] \propto -[F]^n.[O]^m.e^{E/_{RT}} \qquad \textbf{(xix)}$$

With $[F] = x_F.\frac{p_0}{R_U.T_0}$ and $[O] = x_O.\frac{p_0}{R_U.T_0}$

Substituting into equation xviii gives:

$$\frac{\dot{\text{N}}}{V}[F] \propto \frac{1}{\Phi Y_F}.\left(\frac{p_0}{R_U.T_0}\right)^{n+m}.x_F^n.x_O^m.e^{E/_{RT}} \qquad \textbf{(xx)}$$

This equation is then applied to a kerosene fuel for both rich and lean mixture types to give the values for x_F and x_O in each case:

Lean:

$$\frac{\dot{\mathrm{N}}}{Vp_0^{n+m}} \propto \frac{1}{T_0^{n+m}}\frac{1}{Y_F}.(1 - Y_F)^{n+m}.\Phi^{n+m-1}.e^{E/_{RT}} \qquad \textbf{(xxi)}$$

Note, this formulation corresponds with Lefebvre, equation 2-5, but it differs from Strehlow's equation 6-11 which appears to be fundamentally flawed (cf. RHS must = 0 at $Y_F = 1$.)

Rich:

$$\frac{\dot{\mathrm{N}}}{Vp_0^{n+m}} \propto \frac{1}{T_0^{n+m}}\frac{1}{Y_F}.(1 - Y_F)^{n+m}.\Phi^{n+m-1}.e^{E/_{RT}} \qquad \textbf{(xxii)}$$

Which corresponds with Lefebvre, equation 2-7.

3.2. Validation and Application of the Models

The aforementioned idealised gas cycle and well stirred reactor models were then used to produce the results that follow in this subsection. The measured data employed in the formation of these graphs was obtained during engine test runs carried out by Nigel Bester during his investigation into the performance advantages of low aromatic fuel [5] on the SAFL T63 gas turbine. This data is displayed in Table 1, Table 2 and Table 3 below.

Table 1: Gas Turbine Test Results – Set 1

Fuel	Power (KW)	T Inlet (°C)	Fuel Flow (kg/h)	T Exhaust (°C)	ʎ Actual	A/F Actual	Air Flow kg/s
Jet A1	15.53	20.20	26.69	457.40	6.34	93.01	0.69
	120.53	24.60	62.50	532.90	4.74	69.56	1.21
	130.11	24.40	65.55	541.90	4.63	67.89	1.24
	139.98	25.60	69.12	553.40	4.52	66.27	1.27
	152.07	25.70	72.91	564.50			
SPK	16.53	21.20	25.81	464.05	6.17	92.67	0.66
	103.56	24.80	56.07	528.90	4.79	71.98	1.12
	120.37	25.60	61.06	539.60	4.64	69.64	1.33
	127.99	25.00	63.35	546.10	4.55	68.32	1.35
	134.02	25.20	65.54	551.30	4.49	67.49	1.23
	144.66	25.80	68.66	559.30			

Table 2: Gas Turbine Test Results – Set 2

Fuel	Power (KW)	T Inlet (°C)	Fuel Flow (kg/h)	T Exhaust (°C)	ʎ Actual	A/F Actual	Air Flow kg/s
Jet A1	14.67	23.95	25.76	409.05	6.17	90.49	0.65
	118.11	27.60	61.91	480.90	4.43	64.97	1.12

	130.00	28.20	65.88	495.90	4.28	62.77	1.15
	144.41	28.40	70.47	516.80	4.15	60.86	1.19
SPK	15.42	24.75	25.06	404.95	6.28	94.22	0.66
	120.03	29.40	60.75	482.70	4.45	66.74	1.13
	131.59	30.30	64.79	499.60	4.25	63.81	1.21
	142.68	30.20	67.84	513.30	4.18	62.76	1.24

Table 3: Gas Turbine Test Results – Set 3

Fuel	**Power (KW)**	**T Inlet (°C)**	**Fuel Flow (kg/h)**	**T Exhaust (°C)**	**ʎ Actual**	**A/F Actual**	**Air Flow kg/s**
Jet A1	15.26	25.28	23.10	404.60	7.25	106.36	0.68
	125.18	63.33	27.00	483.30	5.25	77.07	0.58
	135.58	66.55	26.80	495.60	5.08	74.50	0.55
	147.59	70.74	27.30	513.70	4.87	71.41	0.54
SPK	16.42	25.37	21.50	398.00	7.25	108.93	0.65
	125.07	61.98	25.90	481.20	5.21	78.21	0.56
	134.84	64.94	25.90	492.30	5.05	75.86	0.55
	144.89	68.52	26.30	505.10	4.90	73.58	0.54
	153.69	70.95	25.70	516.75	4.75	71.33	0.51

3.2.1. Exhaust Temperature

The idealised gas cycle model was initially used to compare exhaust temperatures obtained via measurements for a range of experimental test points with those predicted by the model. Exhaust temperature when running on SPK fuel was predicted for a given power, inlet temperature and fuel flow rate. These given values were selected to coordinate with the data collected during test runs of the engine. A 45 degree linear correlation (indicated by the dashed grey line in Figure 16) indicates the ideal case for model validity. The dashed blue line in the same figure shows the correlation between the predicted data points, while not an ideal match, the results are within an acceptable range thus providing verification of the model's performance. The exhaust temperature predicted by the model shows a uniform discrepancy of 10°C on each result. Unshielded thermocouples were used to measure exhaust temperature in the gas turbine therefore the temperature discrepancy could be attributed to a higher temperature indicated by these sensors. A dashed red line displays the correlation for the data results, each of which has been compensated by 10°C.

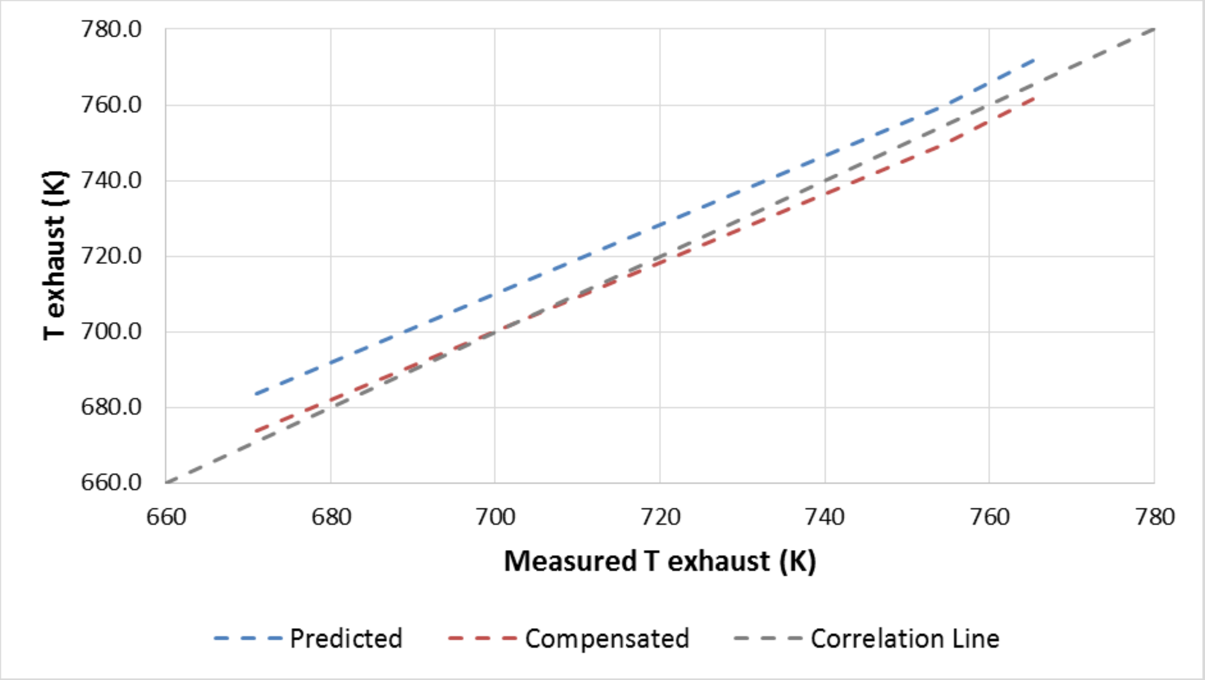


Figure 16: Measured vs predicted exhaust temperature

3.2.2. Air Flow Rate

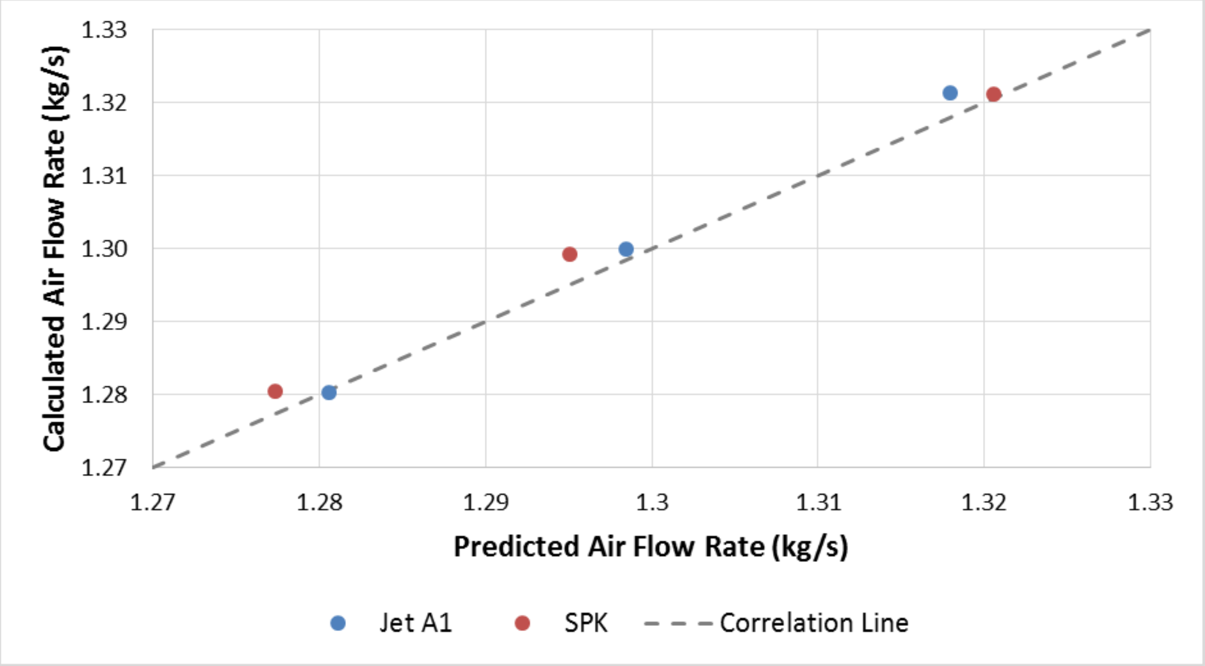


Figure 17: Predicted vs calculated air flow rates

It was possible for the ideal gas cycle model to give the values that were not measured on board the engine or were difficult to measure. It was necessary to obtain a means to determine the air flow rate through the engine. One means of achieving this would be to install a mass air flow sensor, however one of the main disadvantages of including this sensor is that it disturbs the air flow in which it is located. Using the model to predict these values offers an alternative that does not have this disadvantage.

Figure 17 shows the dashed grey ideal correlation line between the calculated and predicted air flow rates. The air flow rate labelled in Figure 18and Figure 19 as the “Calculated Air Flow Rate” was calculated using experimental data obtained during engine runs, namely from the measured fuel flow and measured lambda values. Data for the “Predicted Air Flow Rate” was predicted by the theoretical model based on the measured output power and inlet and exhaust temperatures. The data points for air flow rate when the engine is run on Jet A1 (blue) and SPK (red) are shown clustered around this line indicating a reasonable correlation between the calculated and predicted values. Thus the model may be used to predict air flow rates through the engine.

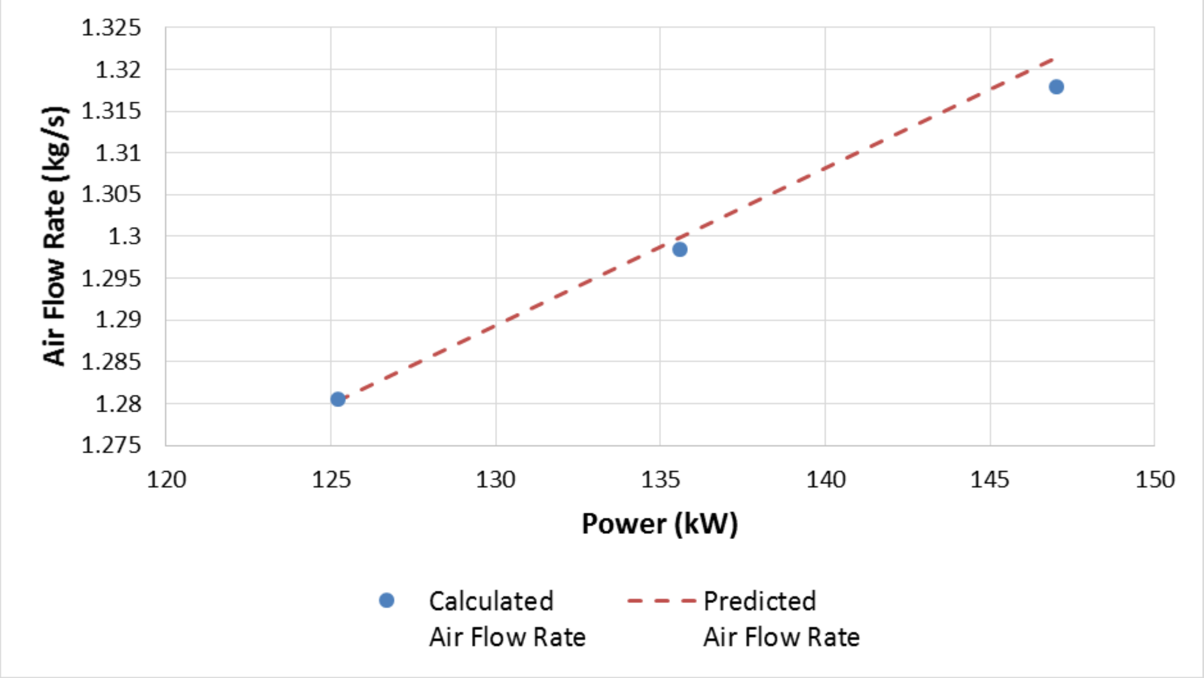


Figure 18: Comparison of calculated and predicted air flow rates- Jet A1

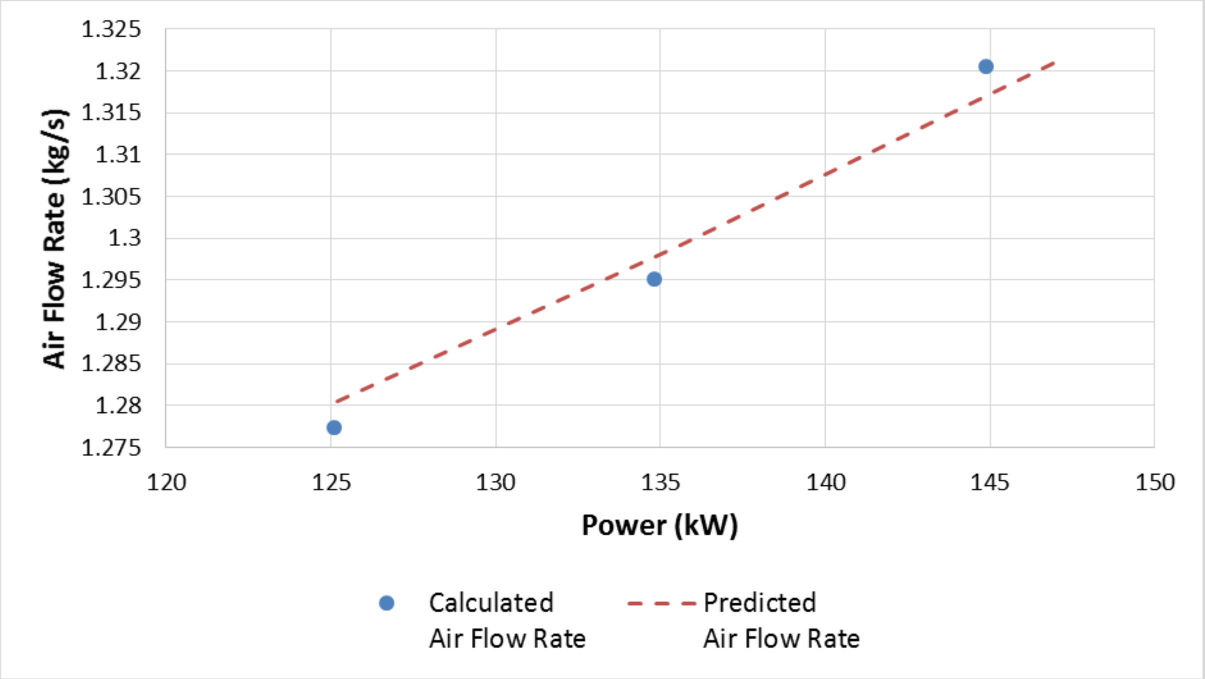


Figure 19: Comparison of calculated and predicted air flow rates- SPK

Figure 18 and Figure 19 further portray the capability of the model to predict air flow rates through the engine. Figure 18 compares the calculated and predicted air flow rates for the engine when running on Jet A1, while Figure 19 shows the same but for an SPK fuelled run. In both cases the predicted values correlate well with those that were calculated from data collected during engine operation.

3.2.3. Adiabatic Flame Temperature

Adiabatic flame temperature within the gas turbine was calculated via the ideal gas cycle model. Values typical of the T63 engine when running at cruising power were applied. Gasses entering the combustion chamber were taken to possess an initial temperature of 230°C at an absolute pressure of five atmospheres after compression. Figure 20 depicts AFT values taken over a range standard in the combustion chambers of aero gas turbines. The T63 is endowed with a rich burning combustor, therefore the AFT in the combustor is higher than that of more modern lean burn combustors.

Arrows indicate the zones of rich and lean burning as well as the flammability limit. The region in which a typical controller will operate is also indicated on the graph with points at which ground idle and full load are applied.

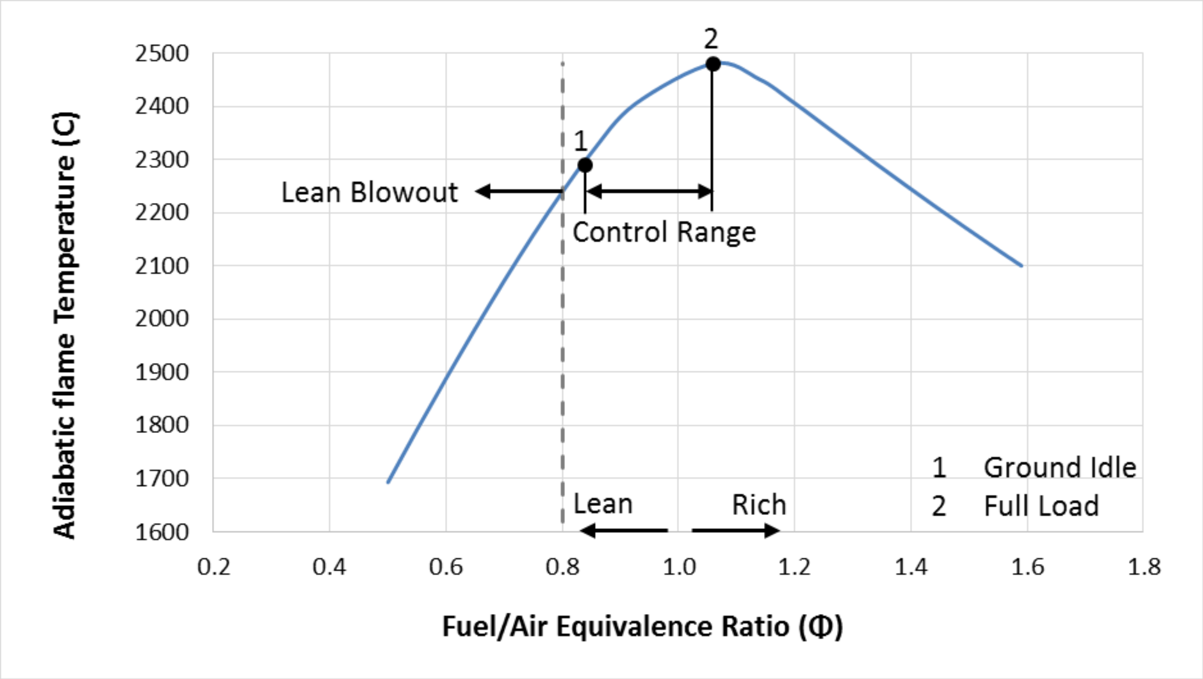


Figure 20: Adiabatic flame temperature for Jet A1

3.2.4. Flame Extinction

Results displayed in this section were obtained using the well-stirred reactor model to obtain insights into the lean flammability limits and effects of blowout on the engine. The general order of pressure dependence n = 0.75 and m = 1.0 were selected in accordance with Lefebvre. A typical value of E/R = 15000 and an initial temperature of 230°C were employed to produce the results demonstrated. This is the temperature at which gases enter the combustion chamber of the T63 gas turbine after compression.

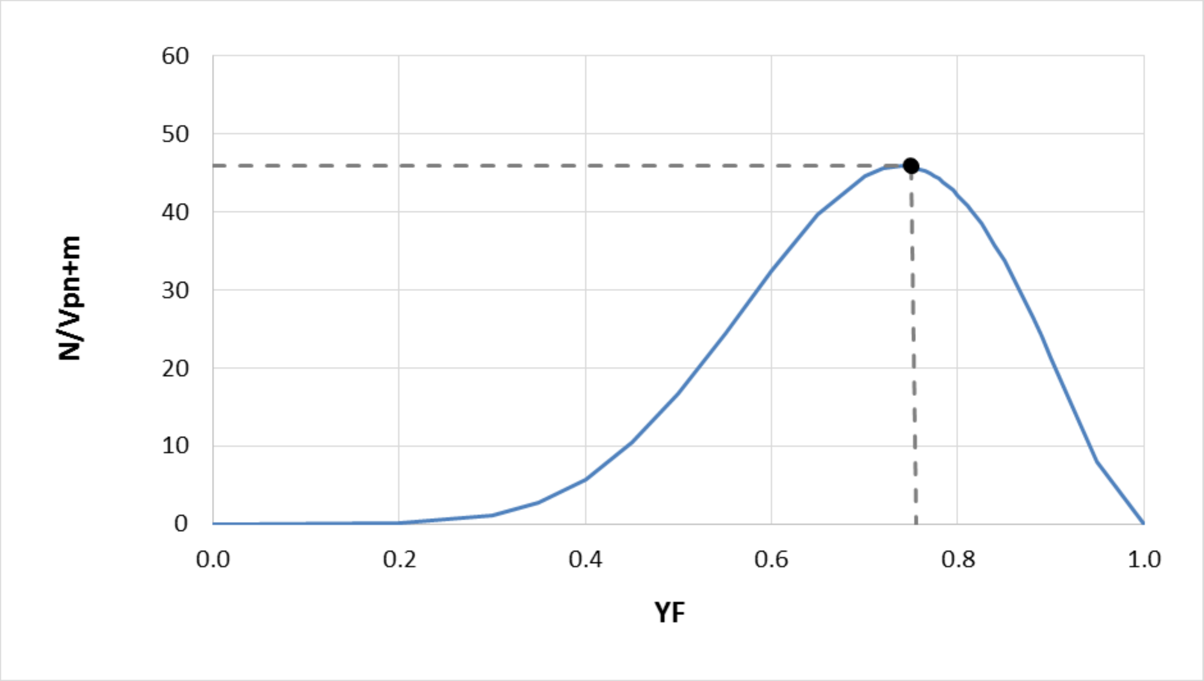


Figure 21: Flow rate vs efficiency

Blowout occurs within the reactor when the rate of heat release due to the combustion reactions is no longer sufficient to raise the incoming gasses to a temperature at which the chemical reactions will continue to occur. Figure 21 shows a plot of the molar flow rate parameter on the vertical axis versus the fuel fraction consumed in the reactor on the horizontal axis. The curve produced represents the theoretical solution for equilibrium conditions irrespective of operational stability in the engine. Blowout will occur for flow rates above those given by the curve. The peak value, indicated by the black data mark in Figure 21 portrays the limiting, maximum flow operating point of the gas turbine's combustor. The portion of the curve falling to the left of this point depicts unrealistic behaviour outside of stable operating parameters.

By considering a range of fuel/air equivalence ratios and combining the calculated AFT shown in Figure 20and the associated blow out point depicted in Figure 21, it was possible to construct a stability envelope as is illustrated in Figure 22. The arrow indicates the region of stable combustion for the T63 gas turbine. The envelope indicated in this graph defines the lean and rich extinction as well as the blow out limits.

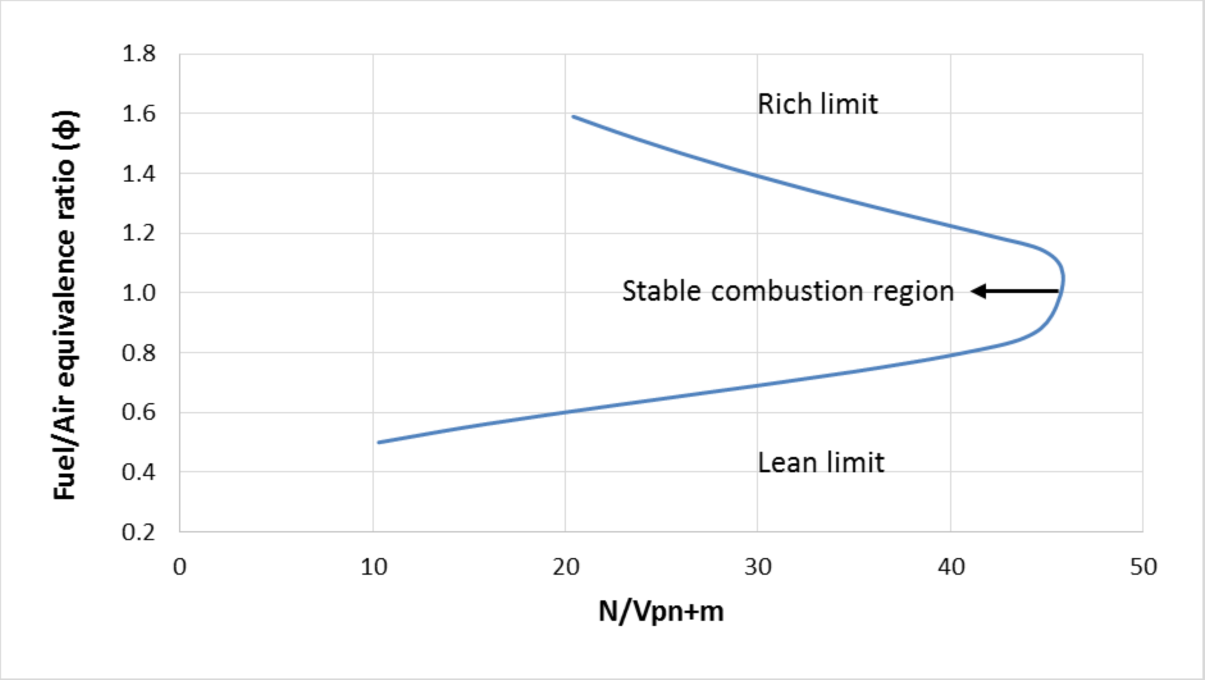


Figure 22: Calculated stability loop

To determine extinction limits for the fuels during future test procedures fuel to the engine will be rapidly reduced. Due to inertia of the rotating components the response time of the compressor would be comparatively slow resulting in a transient lean operation and potentially a blowout of the flame. The combination of reduced fuel flow and a maintained level of air flow through the engine will result in a momentary decrease in adiabatic flame temperature, illustrated in Figure 20, and a corresponding drop in the turbine inlet temperature. At the point of blowout the combustion process will be reignited and standard operation recommenced thus bringing temperatures back to the original levels.

The combustors of aero derivative engines have pattern factors and radial profiles that take into account the possibility of blowout and relight in flight. This ensures that material selection and design of the combustor and turbine blades is resilient enough to cope with the associated thermal stresses. A variety of fuels are to be tested thus it should be noted that fuel type has an insignificant effect on the pattern factor in the power output range at which pattern factor is most significant. Determination of the rich blowout limits is more hazardous, especially at high pressures, as there is a risk of damaging the combustor liner and ducting of the test cell due to the rise in temperatures associated with rich combustion. When undertaking testing of the extinction limits and their effects on the engine the operator would be well advised to exercise extreme caution or better to avoid testing approaching the rich flammability limits.

4. Preliminary Investigation of the Design Problem

The primary goal of this thesis was to design an electronic control system for the T63 gas turbine. A planning phase was the first step in the design process. Tools utilised during the planning process were the Work Breakdown Structure and the Gantt chart. The Work Breakdown Structure dissembled the project into smaller more manageable tasks while the Gantt chart gave a timeline for the execution of each of the aforementioned tasks (these can be found in Appendix C).

Hereafter are the stages that formed a part of the remainder of the initial design process. Design requirements stemmed from stakeholder input and knowledge accumulated in the literature review and control sections. Design concepts were formulated based on these specifications coupled with information drawn during characterisation of the existing system.

4.1. Identification and Formulation of Design Requirements

A consultation with the project stakeholders and stipulations laid out in the design brief were used to compile a list of user requirements and specifications (see Table 4). Justifications for each of the specifications can be found in Appendix C.

Table 4: User requirements and Specifications

No.	Description	Desired	Achieved	Demand/ Wish	Rev	Ref Section
1	**Functions and Features**					
1.1	Reconfigurable	Yes	Yes	W	0	B.2.2
1.2	Accuracy	< 0.5%	Cori Flow = 0.2% LFM 2003 ≤ 0.3%	D	0	B.2.2
1.3	Repeatability	Yes	Yes	D	0	B.2.2
1.4	Manual Override	Yes	Yes	D	0	B.2.2.3
1.5	User Interface	LabVIEW	Yes	D	0	B.2.2.4
1.6	Automatic Start Up	Yes	Yes	W	0	B.2.2.5
1.7	Full Control of Fuel Flow rates	Yes	Yes	D	0	B.2.2.6
2	**Environmental Specifications**					
2.1	Multi-Fuel Compatibility	Yes	Yes	D	0	B2.1.4
2.2	Operating Temperature Range	In Test Cell: 0 C to 40°C	**Cori Flow**- 70°C **LFM 2003**- 50°C **Swagelok Series 141 &142**– 65°C **MAC 900 Series**- 50°C	D	0	B.2.1.2

			Swagelok 130 Series– 93°C			
2.3	Supply Voltage	5V/12V/24V/220V	24V/220V	W	0	B.2.1.3
2.4	Protection Rating	Fluid Leak Protection	**Cori Flow**- IP65 **LFM 2003**- IP44. **Swagelok Series 141 &142** – IP66	D	0	B.2.1.1
3	**Performance Specifications**					
3.1	Pressure	Up to 40 bar	**Cori Flow**– ~41bar **BADGER**– ~41bar	D	0	1.5.1
3.2	Flow Range	~0-100 kg/hr	**Cori Flow**– 2 to 100kg/hr **BADGER**– 2 to 100kg/hr	D	0	1.5.2
3.3	Actuation Time	Safety Related ≤ 150ms	**LFM 2003**- ~100mm/100ms **Swagelok Series 141 &142**– 90° in 2.5s **MAC 900 Series:** Energise- 8ms De-energise- 10ms	W	0	1.5.3
3.4	Sampling Frequency	≥ 5 Hz	10Hz	W	0	1.5.4

4.2. Engine Operating Parameters and Malfunction

Strict limits and operating parameters must be complied with when running a gas turbine to avoid operation outside of the thermodynamic and material limits of the engine. To this end there are a number of variables which need to be carefully monitored during the course of engine operations to ensure correct functioning of the engine and its auxiliary systems thus preventing damage. These variables are temperature, speed, pressure and torque. The electronic control unit must ensure that these be kept within the acceptable limits laid down by the engine manufacturer [37], [38], [39]. These limits are listed below.

4.2.1. Temperature

Temperature limits were set to prevent damage to various components of the engine as well as some of those built into the test cell. Oil temperature limits keep the oil from degrading and maintain it in the required viscosity range.

The temperature of gases entering the turbine section of the engine are the highest experienced within the gas turbine. These turbine inlet temperatures (TIT) are therefore a limiting factor that must be accounted for when operating the engine. These inlet temperatures are difficult to measure however the temperatures of the gasses leaving the turbines are much easier to access and can be related to the more critical TIT. The Allison engine company therefore installed a thermocouple harness at the turbine outlet which averages the temperature across this region. Limits applied to this turbine outlet temperature TOT) prevent damage to the combustor liner and turbine blades while the temperature of the exhaust gasses in the ducts was limited to prevent overheating of the test cell extraction fan. The applicable limits are listed in Table 5.

Table 5: Temperature limits for T63 installation

Measurement	Upper Limit °C	Lower Limit °C
Engine Stabilised TOT	749	350
Mixed Exhaust Gases	200	None
Engine Oil Out	107	0
PTO Oil Out	107	0
Dyno Water Out	60	1

4.2.2. Speed

Speed limits were set to protect the engine drive train components from being damaged as speeds experienced that are excessively low or high lead to issues such as vibration that cause physical harm. Figure 23 depicts the maximum allowable output shaft speeds in relation to the turbine outlet temperature as laid down by the engine manufacturer [37].

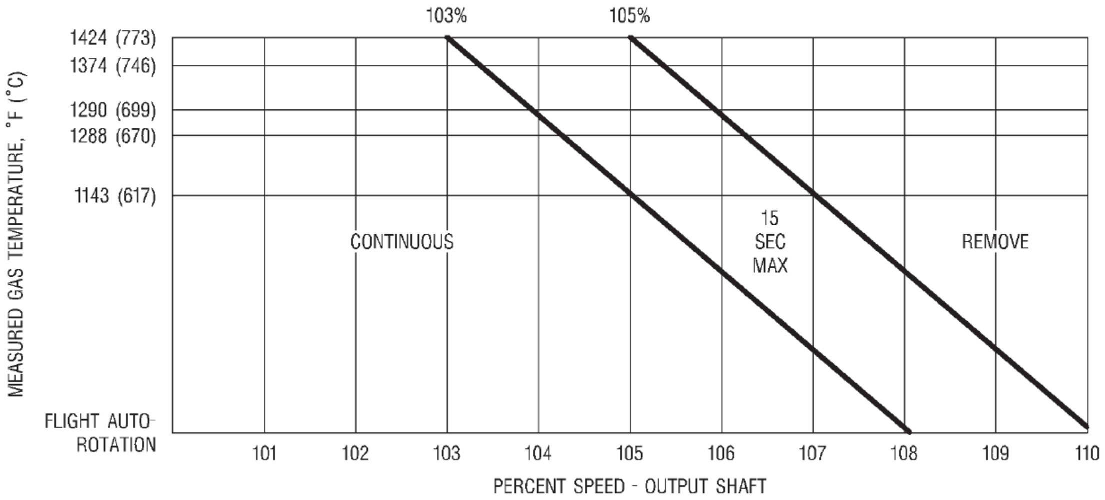


Figure 23: Maximum allowable output shaft speeds

Table 6: Speed limits for T63

Measurement	Upper Limit %	Lower Limit %
N_1	104	None
N_2 @ Idle	71	59
N_2 @ Normal Operation	102	98
N_2 @ Loss of Load	120	N/A

4.2.3. Pressure

A number of pressure variables need to be monitored throughout engine operation to ensure correct functioning of the various associated subsystems. The engine oil and fuel supply pressures have been specified by the manufacturer of the gas turbine to ensure supply needs are met throughout the engine. Additionally an eye needs to be kept on the engine torque sensor pressure limits as these give the operational range of pressure-power correlation. These aforementioned limits are recorded in Table 7.

Table 7: Pressure limits for T63

Measurement	Upper Limit (Bar Gauge)	Lower Limit (Bar Gauge)
Engine Oil	8.96	6.21
PTO Oil	1	0.5
Engine Torque Sensor	6.89	2.07
Fuel Supply	0.7	0.4

(Note: PTO = Power Take-Off)

Likewise to prevent malfunction of the dynamometer and ventilation system the water supply pressure (~2bar gauge) and ambient test cell pressure need to be monitored. Ambient test cell pressure should be operated at a slightly lower pressure than atmospheric; this prevents the escape of exhaust gases into adjacent rooms, such as the control room.

4.2.4. Torque

Records of the engine torque readings were required in order to determine power output by the engine. The dynamometer attached to the output shaft of the engine gave an accurate indication of the engine output shaft speed and torque. The torque values attained from the dynamometer were highly reliable. These readings were in agreement with those of the engine torque sensor power which is obtained through a specific torque oil pressure reading. This specific torque oil pressure reading is proportional to engine torque. The applicable torque limits are entered in Table 8.

Table 8: Torque limits for T63

Measurement		**Nm**	**Upper Limit (Bar Gauge)**	**kW**
Torque	Continuous	337	5.86	212
	30 min limit	397	6.89	250
	10 sec limit	434	7.52	273

4.2.5. Acceleration Rates

Rates of acceleration that are too rapid can result in detrimental effects such as compressor surge and/or hot streaking that are further discussed in this section. The acceleration rates should therefore always be kept within the bounds set by the engine manufacturer.

Compressor surge in a gas turbine is a complete stall or reversal of airflow over the compressor either due to a pressure build up at the compressor outlet that exceeds the prescribed limits, or alternatively the condition results when the compressor is loaded beyond its design capacity. These effects are brought on through abrupt acceleration schedules that cause a mismatch between the compressor and turbines and can result in flameout or structural damage of the engine. The T63 gas turbine possesses a valve that bleeds air off from the compressor outlet, this reduces the pressure build up and improves air flow decreasing the risk of compressor surge. Figure 24 characterises compressor bleed control valve operation with respect to ambient temperature and gas producer turbine speed. Care should be taken when increasing or decreasing engine speeds to avoid the onset of this condition thus additional preventative measures should be implemented when designing the control laws of the ECU.

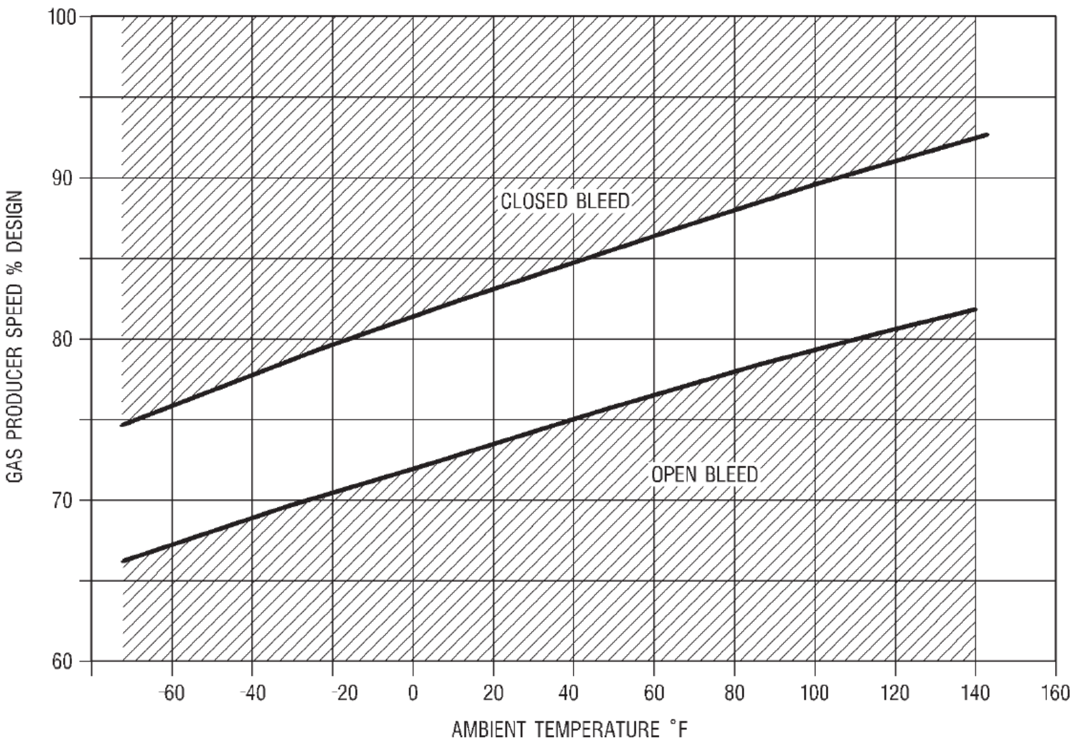


Figure 24: Compressor bleed control valve operation

Hot streaking is a malfunction within the combustion section of a gas turbine that can be brought on by a too rich fuel/air mixture. This phenomenon involves the extension of the combustion flame right up to the turbine inlet occasionally penetrating beyond this point and into the exhaust ducts. Hot streaking has the potential to result in destruction of the engine through material damage caused by overheating.

4.3. Baseline Testing

After establishing the system and user requirements it was necessary to determine the existing system characteristics and properties. Hence baseline testing of the engine and its associated subsystems was required.

The section that follows details the investigation of the gas turbine under control of the original mechanical fuelling system.

Before baseline testing could commence a number of issues that had been encountered during initial test runs needed to be overcome before further progress could be made. Details of all rectifications can be found in the Section 6.1 while the new manual operating procedure can be found on the accompanying disk.

Figure 25 overleaf has been modified to depict the position of sensors incorporated to allow for baseline testing of the existing mechanical fuel control system (Sensors added have been indicated in blue). Pressure transducers were connected into the signal lines of the power turbine governor and gas producer fuel control. These were included for the purpose of determining the reaction time with regards to the alteration of fuel flow rate in response to changes in air pressure signal in each of the control lines, P_r, P_C, P_G and P_y.

A coriolis flow meter, the Micro Motion CMF025, was incorporated into the fuel system situated at the exit of the high pressure fuel pump. A pressure transducer (P_1) was also included here such that the two sensors would provide the information required to specify the valves and flow meter needed for the ECU. Another coriolis flow meter and pressure transducer were positioned in the fuel line leading from the governor of the gas generator to the nozzle of the T63. The flow meter used was a Micro Motion CMF010. Data obtained from these sensors gave the mass flow rate of fuel routed to the nozzle.

Pressure transducers, thermocouples, tachometers and sensors reading engine torque were employed to record data pertaining to engine and subsystem operations. This data was logged at operating conditions ranging from start-up and ground idle to full speed under load. Typical behaviour and readings at each of these points could thus be recorded. This allowed for the development of a control system specific to the SAFL test system set up as well as for purposes of benchmarking during the commissioning and testing phases of the project.

Locations of instrumentation implemented for characterisation of the engine and associated subsystems are pictured in Figure 26.

Results obtained during baseline testing were used to single out a particular concept idea from those originally considered (dealt with in the following section 4.4 Conceptual Phase), thus leading to the first step of the structural design phase which is further discussed in the following chapter.

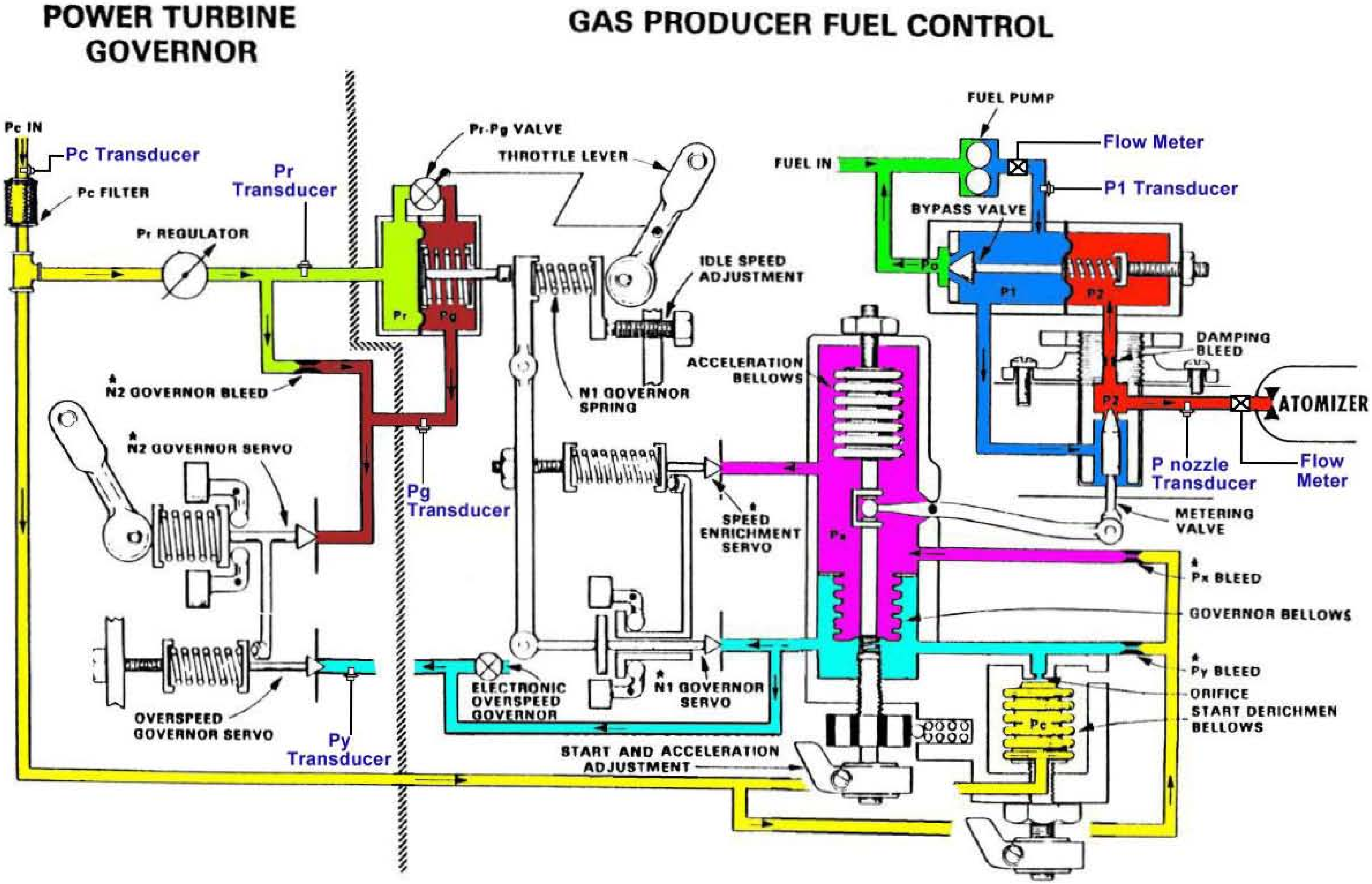


Figure 25: Fuel system baseline testing instrumentation (Modified from [40])

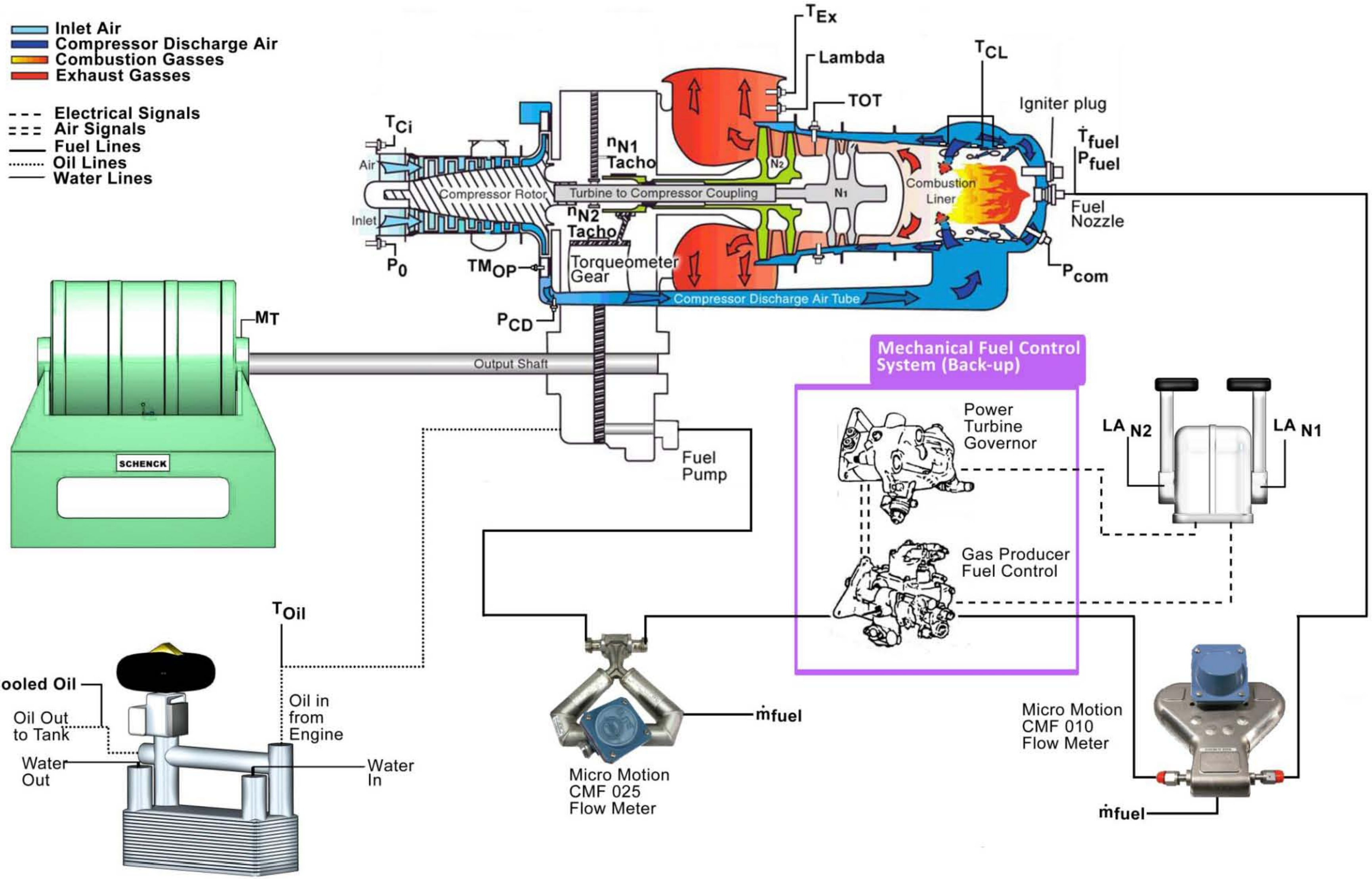


Figure 26: Baseline test cell instrumentation [41], [42]

4.4. Conceptual Phase

The concept formation process included research into the existing fuel control system and similar electronically controlled devices. This yielded a small number of possible initiatives that could be further analysed to determine their suitability as potential solutions for the proposed project. The possible solutions were assessed and weighed using data obtained from the design specifications as well as during baseline testing

The first concept considered required the modification of the mechanical fuel control system of the T63-A-700 made by Bendix. Implementation of this concept could be achieved in several ways, two of which were further investigated to determine their suitability. The first means of modification considered involved obtaining control of the original fuel control system by installing a motor which could be attached directly to the lever connected to the metering valve, such as in Figure 27. This would afford full control of the amount of fuel sent to the engine. The negative side of controlling the system in this manner would be the loss of the overspeed limitation system provided by the N_G and N_P governors because the control lever on which they operate is usurped.

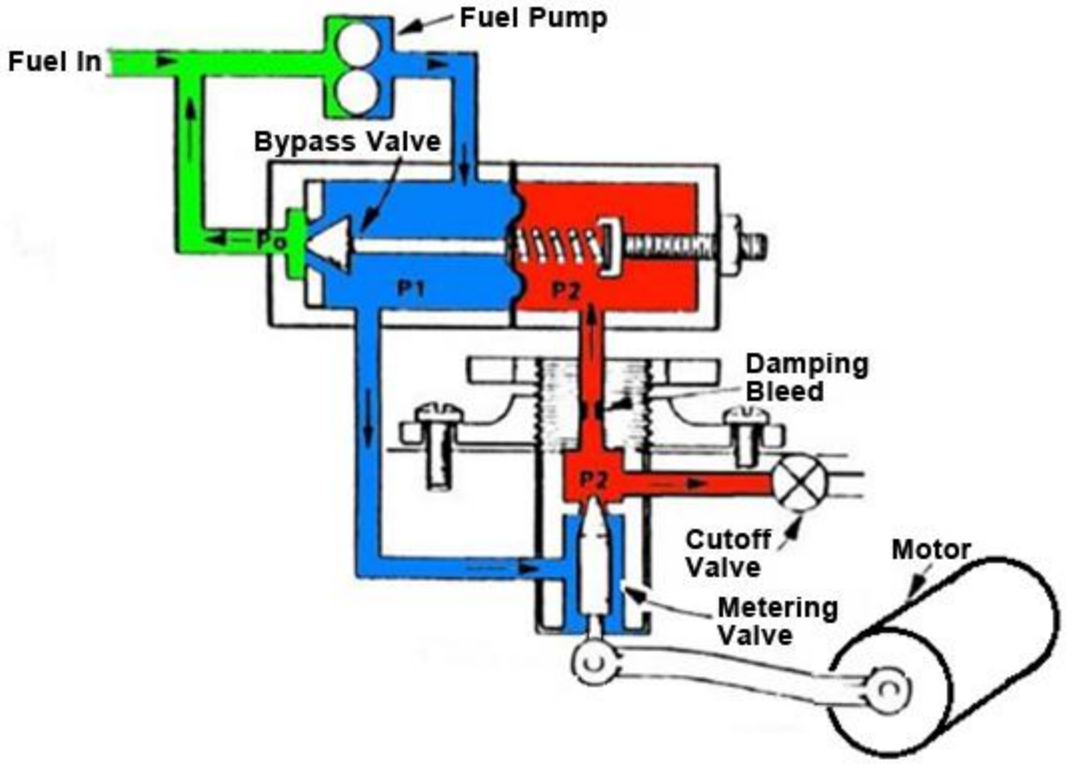


Figure 27: Concept 1a) Bendix modification by direct control of metering valve (Modified from [40])

A degree of control could also be acquired by accessing the pressure lines of the N_G and N_P governors, this was the second option available for modification of the original HMU. This manner of conversion allowed the pressures within the governor system to be altered to induce the desired movement of the metering valve. Fuel scheduling to the gas turbine is achieved by movement of a governor bellows attached to the metering valve (see Figure_ A-6 in Appendix A). Movement of the bellows occurs due to pneumatic pressure and is effected by throttle angle, engine speed and air density.

The governor pressure circuits perform tasks integral to the correct functioning of the fuelling system. Each of these tasks is further investigated here to assess the viability of the pressure control concept. The P_X pressure circuit provides fuel enrichment at a predetermined engine speed while the P_Y circuit responds to throttle angle and P_C (from compressor discharge) adjusts for air density. The purpose of the P_R pressure circuit is to prevent N_G speed undershoot whilst the gas producer is decelerating to ground idle. Lastly, changes of load experienced by the power turbine cause alterations to the fuelling schedule via the power turbine governor. The N_P governor may override the speed governing elements of the fuel control by means of the governor reset section (P_G).

Due to the nature of this proposed control technique it was anticipated that system response may have been slow or inaccurate. During the baseline testing procedure an assessment of engine response time to pressure changes in the pneumatic lines was carried out. Data gathered and analysed is presented below:

Step changes were carried out on both the P_Y and P_R signal lines in order to assess their effect upon the fuel metering system. Figure 28 shows that a positive or negative step change in P_Y of approximately 0.6 bar caused a change of fuel flow rate of ~13 kg/hr in the same direction. The time delay between the step change in pressure P_Y and the effected change in fuel flow rate was 6 ms.

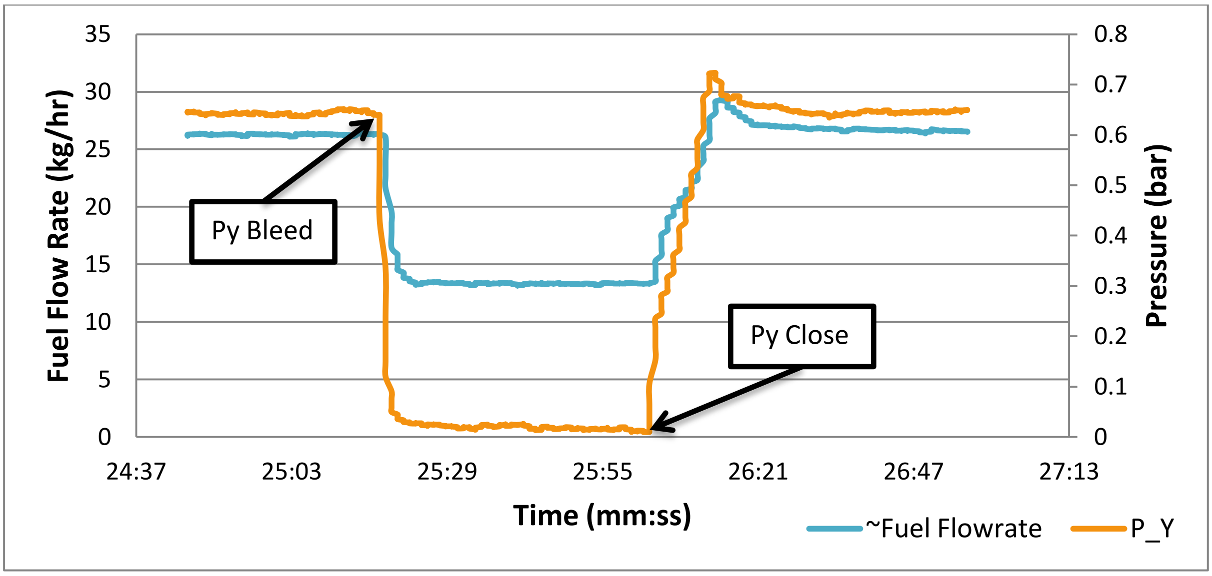


Figure 28: Effect of P_Y pressure change on fuel flow rate

The P_R line was then affected by a step change of ~0.09 bar in both the positive and negative directions. A time delay of 120 ms was seen before any effect on fuel flow rate appeared. Figure 29 indicates that this pressure change in P_R had an indirect effect on the fuel flow rate as is expected due to the layout of the mechanical fuel control system. Within the fuel control system regulated pressure from the P_R line causes pressure changes in the P_X-P_Y pressure differential through a succession of springs and levers. Movement of the metering valve is then caused by changes in this P_X-P_Y pressure differential. This indirect action of P_R pressure changes accounts for the relatively long lead time before changes become apparent.

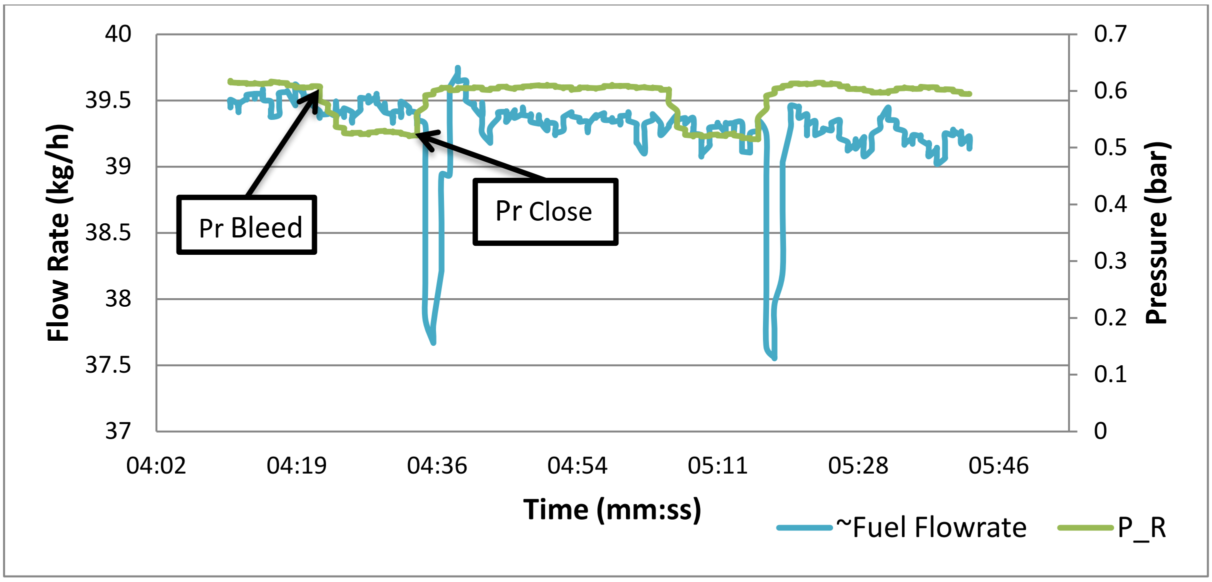


Figure 29: Effect of P_R pressure change on fuel flow rate

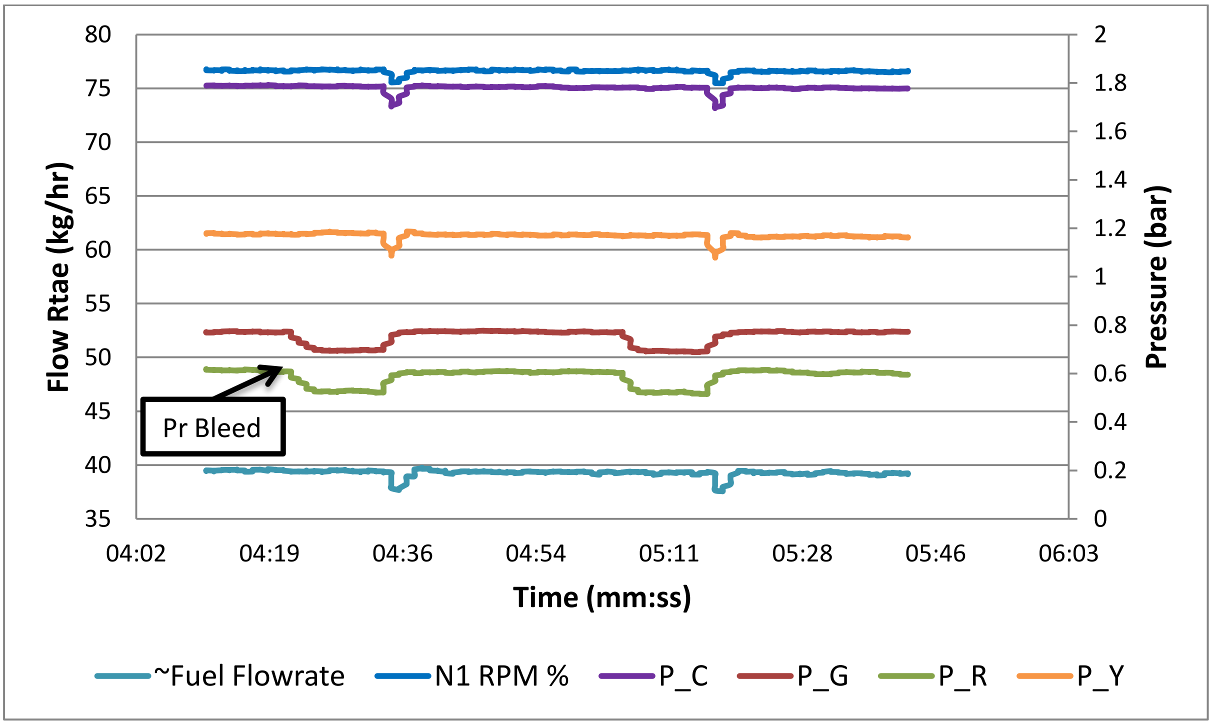


Figure 30: Effect of change in P_R on engine parameters

The gathered data suggested that control of the system via the governor pressure circuits would require fine control of each of the pressure lines. This would entail careful metering of air to and from each of the lines necessitating a complex pneumatic system.

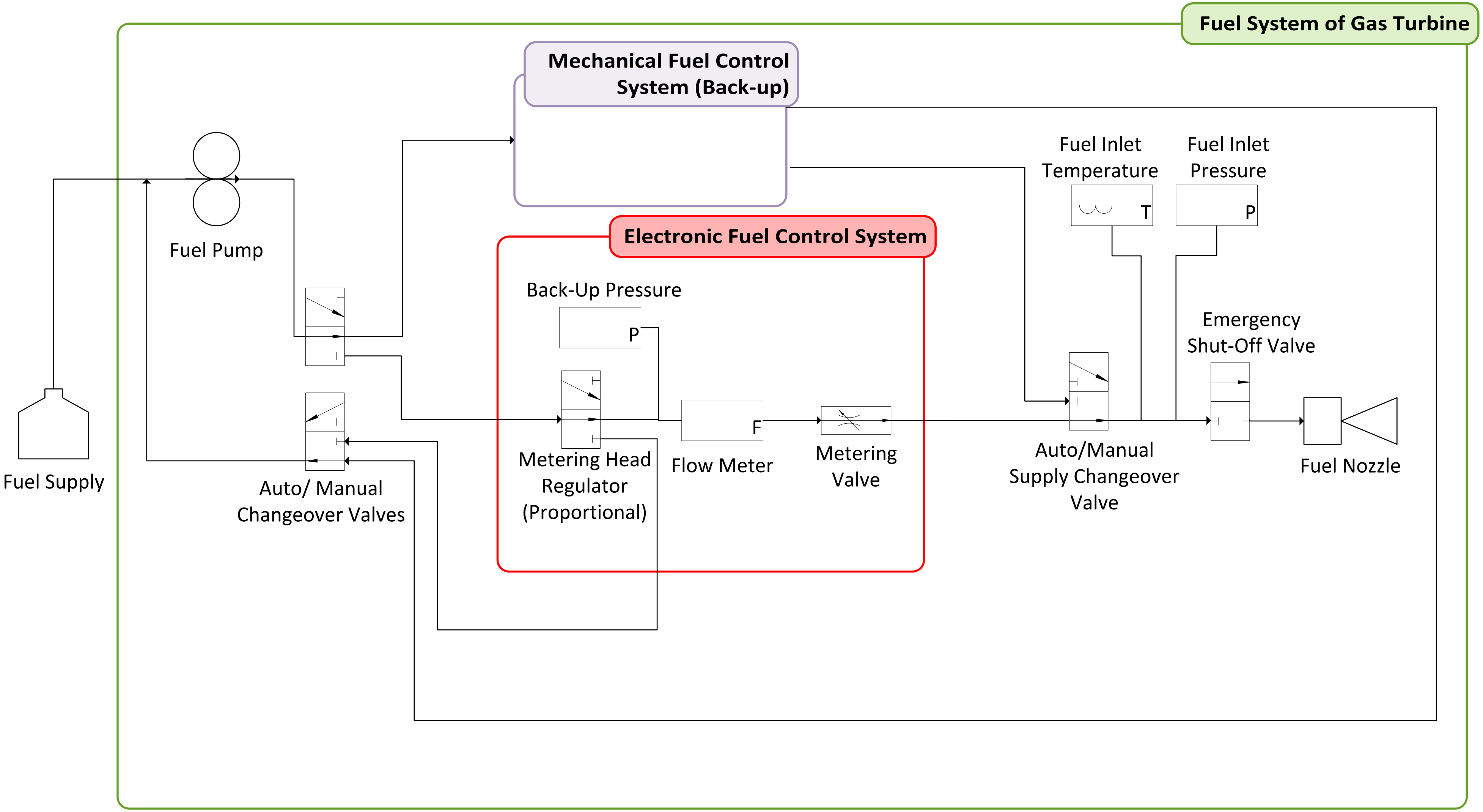


Figure 31: Flow diagram of conceptual fuel system (Concept 2)

Concept two involved the addition of an electro-mechanical system to the original fuel control system. The notion behind this idea was to divert flow exiting the fuel pump through a system of electronic actuators and feedback sensors that could be digitally controlled. The original Bendix control system was to be linked to the fuel lines by means of a pair of three-way valves to form a back-up system. In the event of ECU failure these valves would redirect flow back through the mechanical system. A flow diagram of this system concept can be seen in Figure 31.

The third concept involved the modification of an existing electronic fuel control system to fit the T63 gas turbine installed in the test cell. An investigation was undertaken into units suitable for this application. The Model 250-C30R/3 fuel control unit surfaced as the most appropriate having been built for the latest version of the Model-250 series of which the T63 was the first. This option held appeal because the FCU consists of both a manual back-up system as well as the main electronic fuel control. Another advantage was the space and mountings provided in the housing casing for the electronic actuators and wiring required. A notable drawback was that the system would need to be significantly modified to modulate the fuel flow required for the higher powered C30R/3 (650 shp/485 kW) [43] to that suitable for the T63 (317 shp/236 kW) [44]. The entire fuel control system was supplied as a single unit housed within cast metal, which would make modification troublesome due to restricted access to components.

A decision process was then embarked upon so that one of the three concepts could be singled out as optimal. A Model 250 specialist was consulted and input from this interview taken into account when drawing up a **Q**uality **F**unction **D**iagram (QFD). This QFD analysis was carried out for each of the three conceptual ideas considered; the results are portrayed in Table 9.

A deliberation process endorsed the further development of concept number two. Reasoning behind selection of this concept was follows:

- The original hydro-mechanical control system was to serve as a back-up system in the event of electronic system glitches or failure providing system redundancy.
- Option 3 would require the purchase and modification of the C30R/3 ECU. The acquisition price of this device is outside of the given budget for this project.
- The space saving design of the ECU required for Option 3 prohibits modification.
- Physical modifications of the original fuel control system could be carried out in such a way that only piping would need to be altered, thus a new HMU would not need to be purchased, keeping costs minimal.
- The total score obtained for this concept during the benchmarking QFD process was 28.4, considerably higher than either of the alternate choices. Thus this concept best met both the requirements laid down by the user as well as the technical requirements essential for optimum functioning of the device.
- This concept is the most flexible in terms of creating a custom and reconfigurable device. Parts may be selected individually to suit each required task with cost being

the only limiting factor when selecting parts with improved performance and reliability.

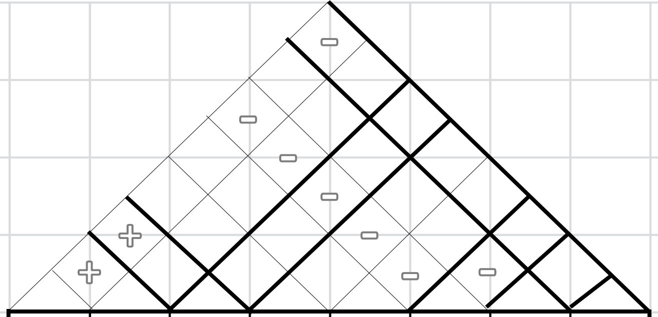
Disadvantages of this concept design were that parts needed to be shielded from the high temperatures associated with the gas turbine combustion as well as from fluid in the case of spills or leaks. A mounting structure needed to be designed for the electro-mechanical devices and actuators.

Table 9: Quality function diagram for T63 electro-mechanical concepts

Key:

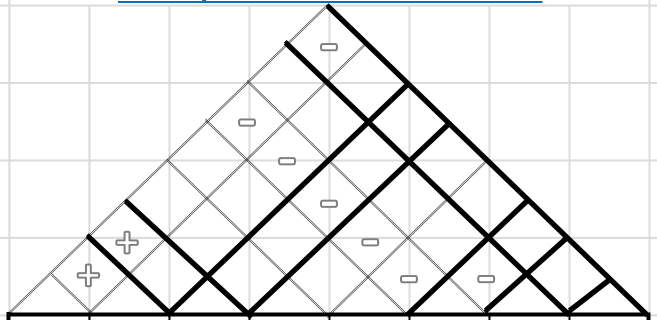
- ▲ Higher = Optimal
- **X** Neutral
- ▼ Lower = Optimal

Concept 1: Bendix Modification



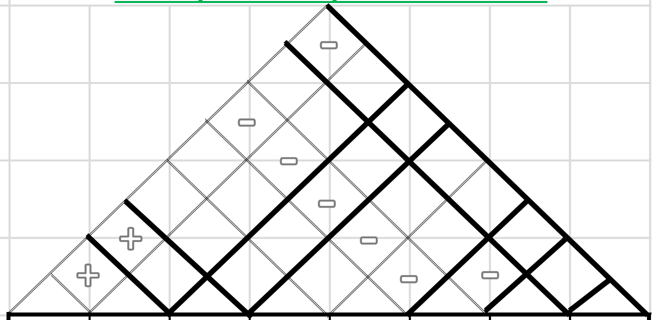
User Requirements	Weighting	Mean Time Between Maintenance (MTBM) (months)	Multiple Fuel Compatability	Sealed Housing	Repeatability (%)	Accuracy (%)	Total Cost (R)	Response Time (ms)	Operating Temperature Range
		▲	▲	X	X	X	▼	▼	X
Reliability	0.1	3	3	3			3		3
Safety	0.3	3	1	9			1		3
Ease of Use	0.2	1	1				9		
Reconfigurable	0.1		1	3	3	3	9	3	1
Cost	0.2	3	1	9	3	3	9	3	3
Labview	0.1							3	
Total	1	2	1.1	5.1	0.9	0.9	5.1	1.2	1.9
Ranking		3	6	2	7	8	1	5	4
Unit		Mths		IP	%	%	R	ms	°C
Target Values		6		54	0.05	0.15	140k	30	0-750

Concept 2: Electronic Addition



User Requirements	Weighting	Mean Time Between Maintenance (MTBM) (months)	Multiple Fuel Compatability	Sealed Housing	Repeatability (%)	Accuracy (%)	Total Cost (R)	Response Time (ms)	Operating Temperature Range
		▲	▲	X	X	X	▼	▼	X
Reliability	0.1	9	9	3			3		9
Safety	0.3	9	3	9			3		9
Ease of Use	0.2	3	1				1		
Reconfigurable	0.1		1	9	3	3	3	3	3
Cost	0.2	3	3	9	9	9	9	9	3
Labview	0.1							9	
Total	1	4.8	2.7	5.7	2.1	2.1	3.5	3	4.5
Ranking		2	6	1	7	8	4	5	3
Unit		Mths		IP	%	%	R	ms	°C
Target Values		6		54	0.05	0.15	140k	30	0-750

Concept 3: C30R/3 Modification



User Requirements	Weighting	Mean Time Between Maintenance (MTBM) (months)	Multiple Fuel Compatability	Sealed Housing	Repeatability (%)	Accuracy (%)	Total Cost (R)	Response Time (ms)	Operating Temperature Range
		▲	▲	X	X	X	▼	▼	X
Reliability	0.1	3	3	9			1		1
Safety	0.3	3	1	9			1		1
Ease of Use	0.2	3	3	1			1		
Reconfigurable	0.1		1	9	3	3	9	3	3
Cost	0.2	1	1	1	9	9	9	9	1
Labview	0.1							3	
Total	1	2	1.5	4.9	2.1	2.1	3.3	2.4	0.9
Ranking		6	7	1	4	5	2	3	8
Unit		Mths		IP	%	%	R	ms	°C
Target Values		6		54	0.05	0.15	140k	30	0-750

Benchmarking of Concepts

Ranking	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
Concept 1	5.1	5.1	2	1.9	1.2	1.1	0.9	0.9	18.2
Concept 2	5.7	4.8	4.5	3.5	3	2.7	2.1	2.1	28.4
Concept 3	4.9	3.3	3	2.1	2.1	2	1.5	0.9	19.8

5. Design & Implementation

Chapter 5 describes the systems created over the course of this thesis. Advantages and disadvantages of the design are listed followed by a review of the ECU that was developed. The chapter is divided into two sections: the first investigates the components of the electro mechanical system, while the second section explores the software and hardware comprising the digital systems. A full specification for the developed system is located in Appendix C, Section 1.4.

5.1. Pros and Cons of Final Design

Weighting the various pros and cons associated with each of the ideas put forward in Section 4.4 sanctioned the decision to pursue the design pictured in Figure 32. This design best fulfilled the requirements set out in the project specifications and provided the following benefits:

1) The HMU was to be preserved, allowing operation of the engine in either manual or automatic mode. The system would serve as a back-up in the event of a power failure.
2) Independent and customisable control allows off map scheduling of fuel.
3) No alterations required to original fuel governing elements thus back up versions of each would not need to be purchased, these parts are both difficult to source and costly.
4) This concept best met both the requirements laid down by the user as well as the technical requirements essential for optimum functioning of the device.
5) Fully customisable and reconfigurable device.
6) Several safety systems incorporated activated either manually and/or electronically. These protect against engine damage under various circumstances.
7) Actuators are electronically controllable and easily integrated into the LabVIEW environment.
8) Flow meter and valve work as a unit to control fuel flow quickly and precisely.
9) System instrumentation senses all relevant system data and forwards this via the data acquisition modules to the control and monitoring systems.
10) Schenck throttle actuator integrates seamlessly with pre-existing Schenck X-act controller and dynamometer.
11) Improved throttle positioning accuracy and repeatability
12) Revised operating mode of dynamometer inherently safe.
13) Signal generation capabilities for frequency testing
14) System redundancy.
15) All management applications and data logged accessible from a single location
16) Automated operation using either the ETA or LabVIEW software decreases operator workload and offers improved repeatibilty of testing.
17) 10 Hz sampling rate gave better achievable control quality and reduced aliasing effects without straining resource capabilities.

18) Digital software and hardware selected to be scalable and modular.
19) Engaging the programmable automation controller (NI CompactRIO) in hybrid mode promoted easier programming, diagnostics and debugging with Scan Interface mode, while offering enhanced performance and reliability of FPGA mode.
20) User friendly graphic interface with push button control.

However the following drawbacks exist:

1) Parts such as the solenoid actuators and flow meter need to be kept away or shielded from the high heats of combustion as well as from any fluids that may cause damage.
2) The three auto/manual changeover valves need to be actuated nigh on simultaneously to maintain the correct fuel flow through the system.
3) Components which require electrical power to function were to be selected so as to fail into a safe mode in which the engine and subsystems would suffer no harm. This specification required non-standard parts with longer lead times for procurement.
4) Running in hybrid mode expanded the time taken to compile code for the FPGA.

It should also be noted that care needs to be taken to isolate electronics and wiring from fluid leaks and moving parts.

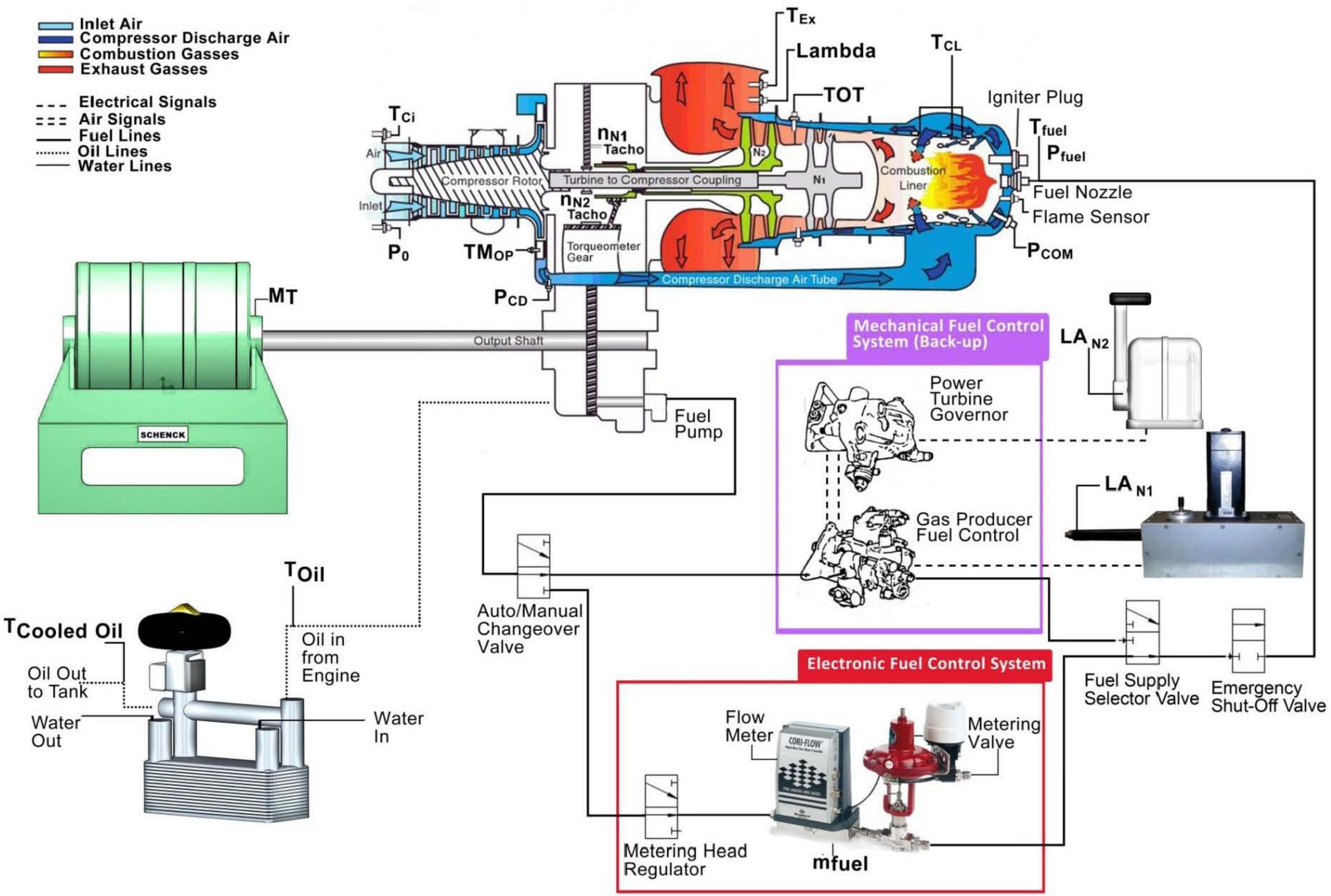


Figure 32: Test cell instrumentation of completed system [41], [45]

5.2. Control Philosophy

The control system of the T63 gas turbine was specified so as to run the engine strictly within safe operating parameters while allowing the fuel scheduling flexibility required of future fuel testing procedures. It sequences fuel to the engine as well as signalling the starter motor and dynamometer to maintain stability across the full range of gas turbine operation. The control system also monitors the gas turbine and auxiliaries to protect against unsafe or undesired responses. The control system meets the following requirements laid down in Table 10.

Table 10: Control system requirements

No.	Requirement
1	Independent backup systems
2	Multiple, independent means of shutting down the engine
3	System failure will result in immediate, safe shutdown
4	Protection against full loss of load with no over speed
5	Redundant control systems
6	Alarms for all system issues

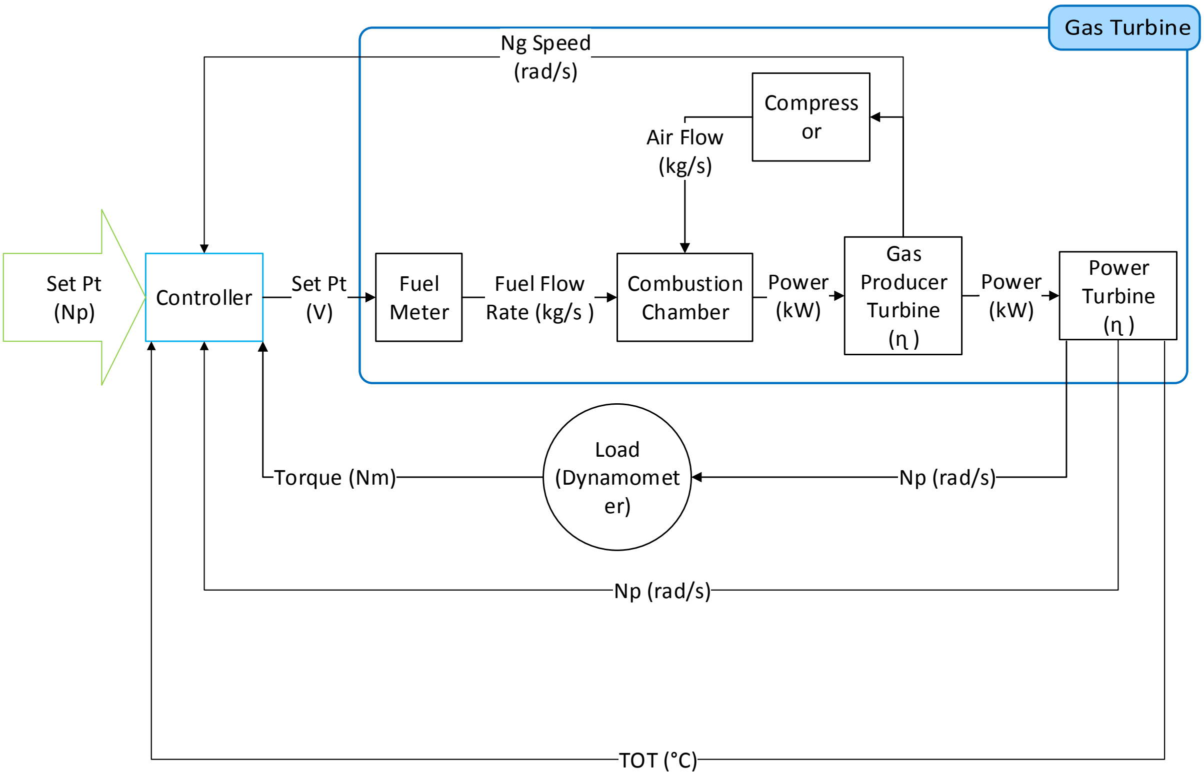


Figure 33: Block diagram of inputs and outputs of model

Figure 33 shows the inputs and outputs of the overall system in relation to requirements of controlled system. Input to the system comes from the operator in the form of a power turbine speed set point. Fuel flow to the system is determined in response to this input as well as to the speed and load requirements. Temperature and acceleration are limited to those specified as within the safe operating region via a strict fuel flow control. These operating limits for temperature and fuel flow are depicted in Figure 34 [46] and are sourced from the engine operating manual (see Section 4.2 for further detail). The control system then passes a voltage to the fuel flow meter indicating a certain fuel flow rate set point. The metering valve is then adjusted accordingly such that the desired fuel flow is passed into the combustion chamber. The closed feedback loop then returns the turbine speeds and torque exerted.

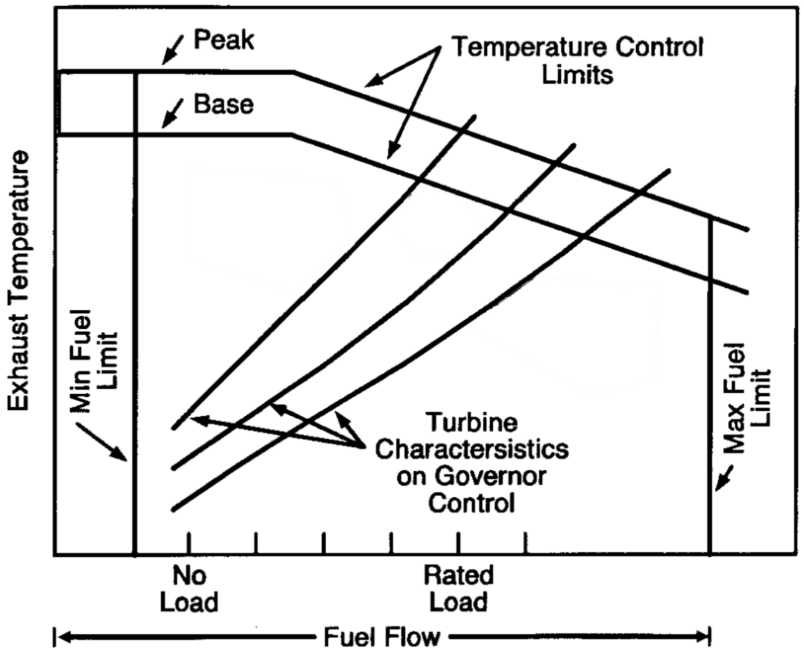


Figure 34: Gas turbine generator controls and limits

Figure 35 focusses in on the fuel controller and its associated laws. There are two engine control laws, one of which is employed at start up and takes the engine up to ground idle state. The engine speed control law then takes over. The control law that was to be facilitated aims to control the engine primarily via manipulation and control of the power turbine speed. The power turbine speed set point was input by the user and proceeds to the controller where the current power turbine speed and load setting are taken into account. The correct fuel flow to achieve the desired power turbine output speed was then to be calculated. The fuel schedules suggested by the separate limit control laws for the gas producer turbine, turbine outlet temperature and acceleration rate are then compared to the fuel flow rate required to achieve the desired power turbine speed. The minimum fuel flow rate suggested by each of these laws shall be what is sent to the engine, thus ensuring safe operation.

Using the system identification method mentioned in section 2.5.6, transfer functions for the three conditions that are to be controlled must be synthesised. The transfer functions are the linear mappings of the Laplace transform of the input, in this case the fuel flow rate, to the Laplace transform of the outputs – temperature, gas producer speed and power turbine speed.

Linearised models of each of these conditions (depicted by the system blocks in Figure 35) can then be constructed around a number of set operating points over the stable range of gas turbine operation to determine the relevant control laws. Using linear control theory a transfer function for the controller could be determined to create the required dynamics for temperature control. The controller provides a fuel flow rate that enforces the set point of the temperature based on this transfer function. The process was to be repeated for both the speed and acceleration controllers. The set point limits for temperature, speed and acceleration can then be defined so as to push the model to 95% of the maximum values for each scenario. The maximum set points for these limiting functions were as follows [37]:

- Temperature: 95% of 749°C = 711.55°C
- N1 Speed: 95% of 51,600 rpm = 50,980 rpm

The desired system dynamics to be achieved through implementation of the engine speed controller were as laid out in Table 11. Ultimately the goal of the control system was to obtain a fast response with no overshoot while maintaining a zero steady state error. These specifications allow for good feedback control of the gas turbine to be obtained by ensuring low-frequency command following and disturbance rejection. The controller should also be insensitive to errors in sensor feedback and show a robust response to high-frequency dynamics. The limiting functions should have faster settling times than the speed control to prevent them from interfering with normal operation. [47], [27], [48].

Table 11: Desired engine dynamics

Specification	Desired Value
Phase-Margin	50°
Gain-Margin	1.5
70% Rise-time	≤ 0.3s
±10% Settling-time	≤ 1 s
Overshoot (%)	≤ 5%
Maximum Steady State Deviation	1 %

The fuel flow rate set points determined by each of the relevant laws can then be put through a minimiser. The controller has been designed in such a way as to default to use of the power turbine engine speed controller during general use as this value would, under normal operating conditions, remain lower than those suggested by the limiting functions. In the case of an event that would cause engine over speed or over temperature the engine speed control law would suggest a value higher than that of the limiting functions. In this case the values suggested by the respective limiting function would take precedence as this value would then be the lowest. In this manner the minimiser results in a low value select function that allows a moving minimum proportional with fuel flow rate.

The final fuel flow limiting function prevents a sudden cut off of fuel flow to the engine, and inevitable flame out, by enforcing a minimum flow rate. Activation of this minimum value was to immediately initiate a safe shut down procedure.

The T63 engine has a bleed valve to reduce the possibility of compressor surge however as an additional preventative measure an acceleration control was to be included in the design of the electronic control unit. This controller ensures that the rate of acceleration may not be extended beyond safe limits.

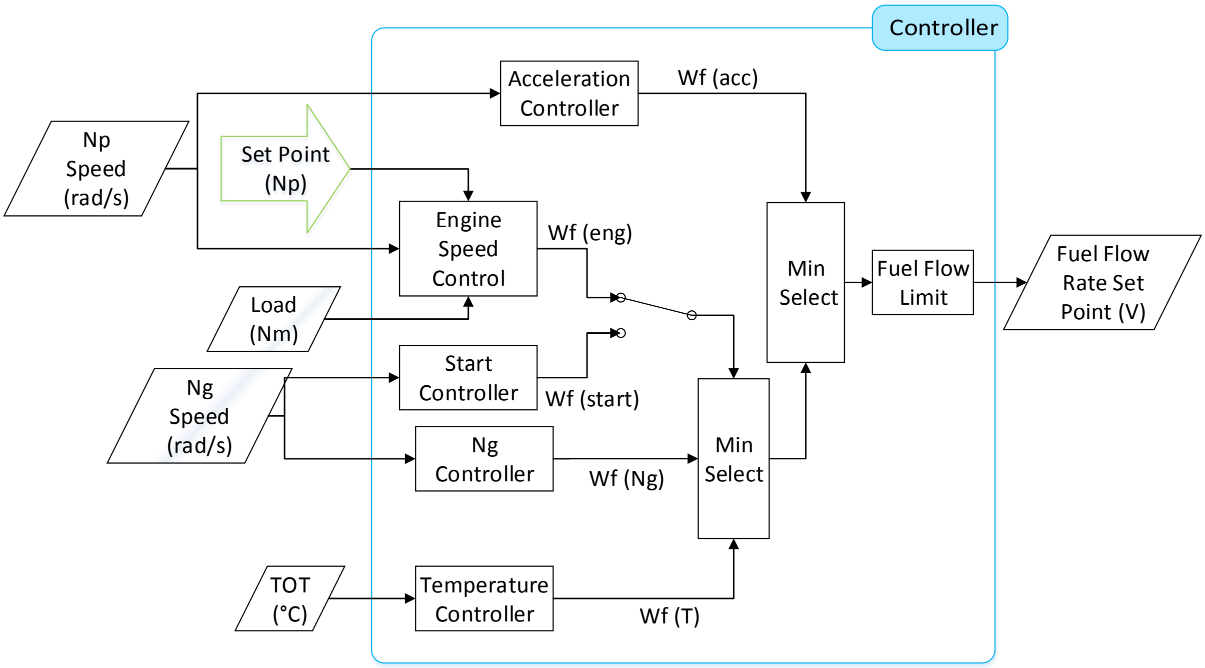


Figure 35: Block diagram showing controller layout

The controller operating map shown in Figure 36 lays out the operating boundaries that the controller must follow in order to keep the engine under stable operating conditions. Safe operating procedures and operating limits for the engine, as laid down in the T63 operating manual [37], [38], were adhered to. These limits are listed in Table 5 to Table 8 in Section 4.2 which describes the engine operating parameters.

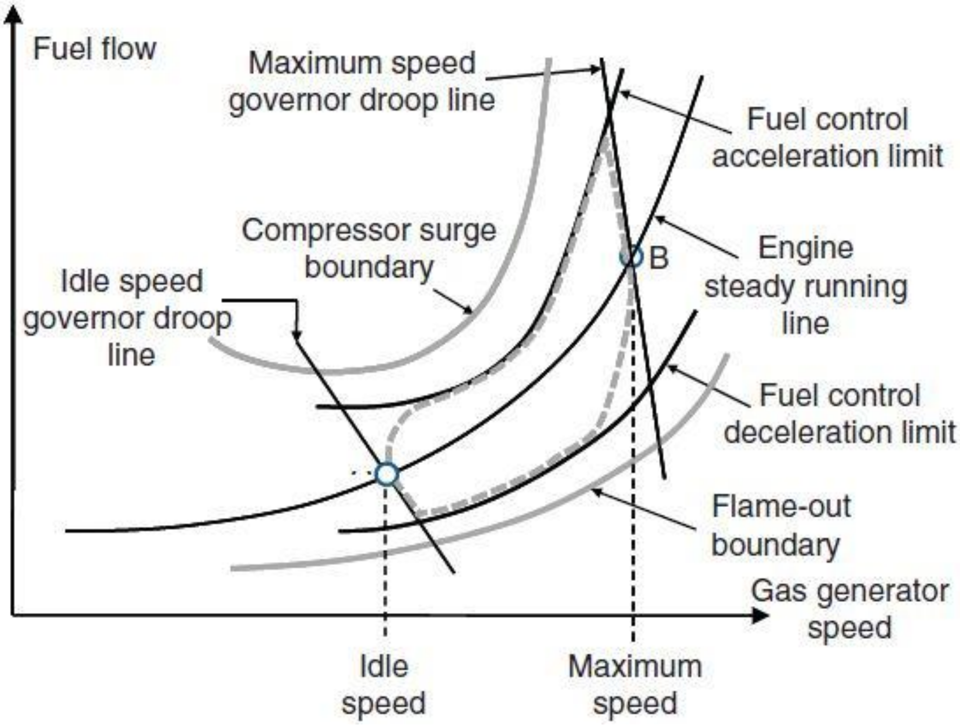


Figure 36: Controller operating map

5.3. Electro-Mechanical System

The electronic control unit of the T-63 needed to integrate the sensors, actuators and other electro-mechanical components with information processing software. The electro-mechanical system gathered data from the environment and system and responded to output signals produced by the digital control system. The following main components were added to the original test cell set up to make up the electro-mechanical system of the gas turbine.

5.3.1. Throttle Actuator

Initial testing of the gas turbine involved investigation of the feasibility of using step testing in forthcoming Phase II of the project. The survey on control theory (Section 2.5.6) indicated that formulation of a control law for the engine would require that the system first be identified and characterised. The simplest option for existing set up would be system excitation of the engine via transmission of step inputs. The human operator was capable of producing reasonable step inputs using the pre-existing lever system. The results from these first tests soon displayed that step testing via a manually operated lever system would not be adequate (See Section 6.2.2 and 6.2.5 for further clarification of testing and results).

This finding led to the inclusion of an electronic throttle actuator, utilised to attain automated control of the T-63's mechanical fuel governing system and thus the engine itself. The automated throttle positioner was capable of a much higher degree of accuracy, precision and repeatability than the manual system could offer.

A selection of actuators was considered for the role however Schenck's LSR 2003 throttle position control unit was the most judicious choice. The unit was a practical and convenient addition to the test cell assembly and integrated smoothly with the X-act Controller of the Schenck dynamometer. Since communications to the X-act controller had already been implemented, it was a simple task to expand these to include those of the LSR 2003.

The unit comprised of a LFM 2003 actuator and the LFE 2003 Control and Power Unit. The actuator replaced the mechanical throttle cable originally linked to the N_G governor lever. The actuator that changes throttle position is electronically driven by an AC servomotor capable of exerting a nominal force of 220N in a linear or rotational motion or combination thereof. The maximum stroke is 120mm or 270 degrees with end stops programmed into the control unit using the configuration program during set up. The motor drives a slide rod connected to a Bowden cable (the LBZ 2000) which forms the junction between the actuator and the throttle lever of the gas turbine. The cable compensates for small alignment faults between the slide rod and lever.

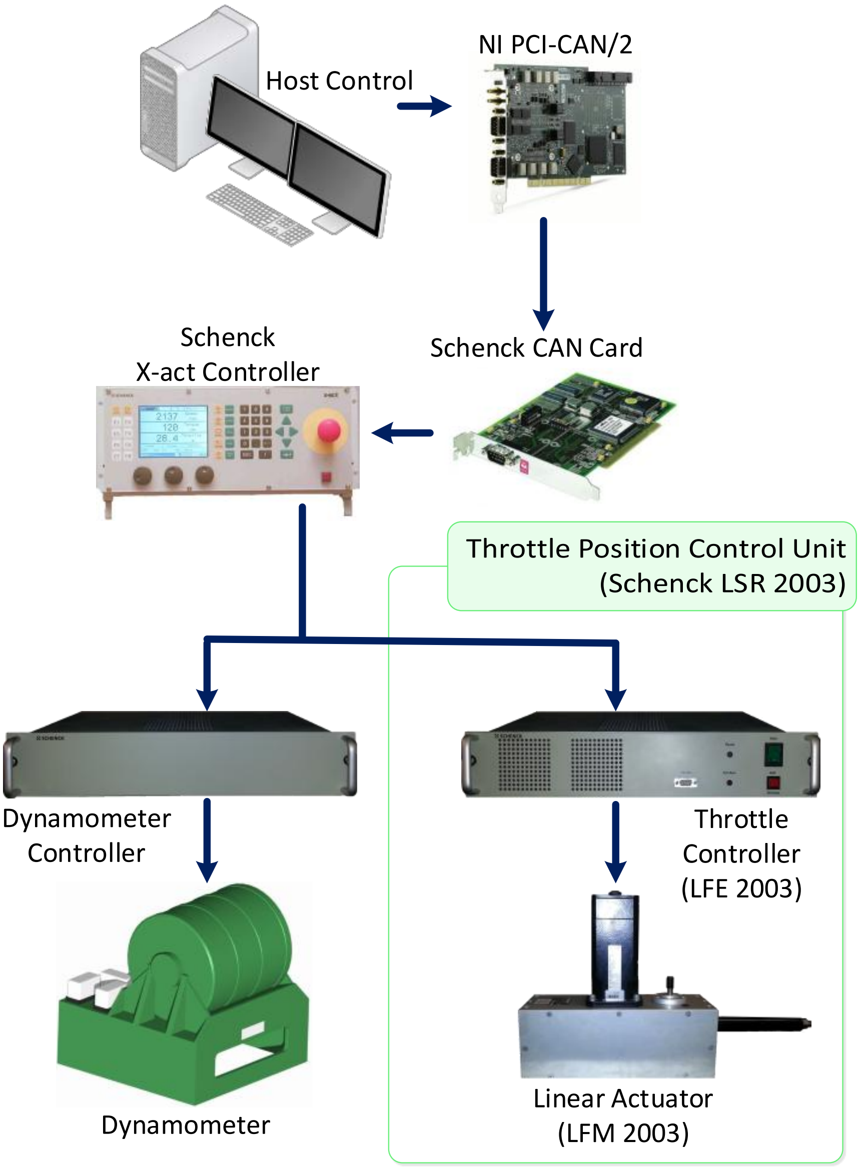


Figure 37: Dynamometer and throttle control systems

Adjustments in throttle position are brought about by the Throttle Position Control Unit which integrates a controller and motor drive section. A 0-10V output signal is transmitted to the linear actuator to produce a change in throttle position between 0 and 100%. Actuation time over a 100mm distance takes approximately 100ms hence it was possible to move the throttle position from 40-95% (ground idle to take-off power) within 55ms, well within the 1 second time allotted by the FAA and EASA regulations mentioned in Section 2.5.4. The engine operating manuals do not specify a rate of acceleration therefore in lieu of these specifications the maximum safe acceleration was matched to that allowed by the original system.

The actuator is specified with an IP 44 protection rating leaving it safe from intrusion by foreign objects and water spray in any direction, it was thus safe to fit the device itself within the engine test cell. Advantages of fitment of this item over the mechanical linkage operated by hand were the following:

- A fast response time
- Requires minimum adjustment and maintenance
- Greater accuracy of data improves the control of fuel demand to the original mechanical fuel governors, which in turn provides better response and performance from the gas turbine.

5.3.2. Safety Valves

When dealing with a manually operated system, the last line of defence in the event of mechanical system failure is the human operator. The reaction time of a person ranges from 143 to 461 milliseconds. On average a person will take 223 milliseconds to assimilate the information and respond [49]. Automated systems obtain far higher response times of only a few milliseconds and are thus often preferable. Three cut off valves were introduced at different locations into the fuel system of the T-63. All three valves were solenoid actuated, two with electro-pneumatic actuators and the last purely electronic. Each had a response time of below 20 milliseconds.

Two electro-pneumatically activated valves were installed directly into the fuel lines of the engine and were of the normally-closed layout. This layout has the advantage of acting as a fail-safe in the event of loss of electrical or pneumatic power, instantaneously closing the valve. These valves must be actuated to the open position during the startup process to permit fuel to pass into the engine. The first of these valves, depicted in Figure 38 as the Supply Valve, admitted fuel into the test cell fuel lines from the fuel store and filtering assembly. Control of this valve was wired to the ETA monitoring system as well as to two emergency buttons located at the control desk and outside the test cell, at the fuel filtering assembly. Fuel was often bled from the system at the filtering assembly to remove entrained air; the switch positioned here thus simplified the bleed process. Prior to fuel entering the combustion chamber it would pass through the second emergency shut off solenoid preceding the fuel nozzle (The Overspeed Valve in Figure 38). The particulars of this valve are discussed in Section 5.3.3.

The third solenoid valve was placed in the Py derichment line of the gas turbine's governing system. This Py Bleed Valve was of the normally-open format and required closure on start up. When deactivated the valve bled air from the governing system causing fuel flow to the engine to drop. As a consequence the engine speed would drop to just below idle conditions. Control of this valve was managed by ETA which was programmed to automatically open the valve as soon as any of the T63's pressure, temperature or speed limits was breached.

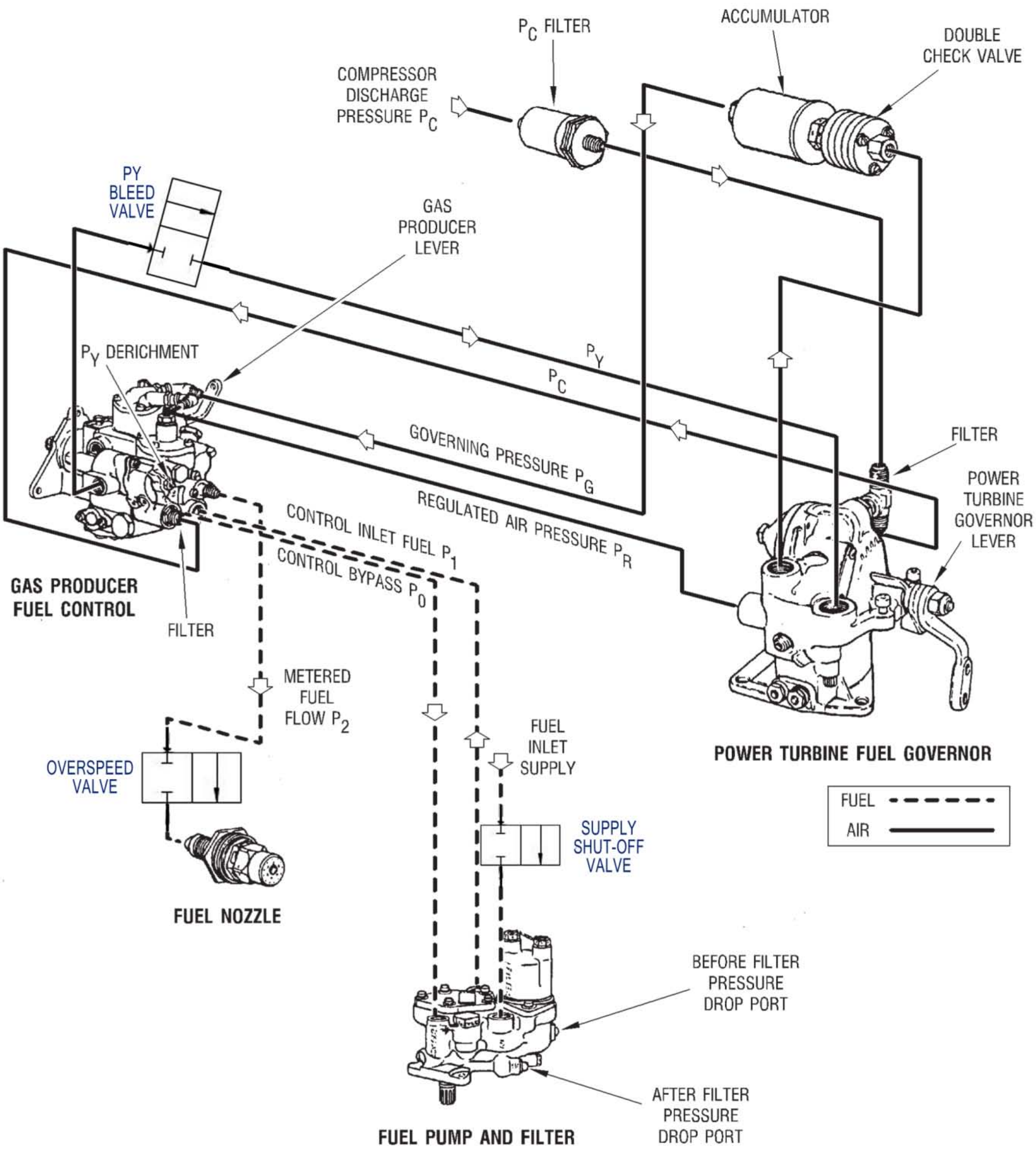


Figure 38: Location of safety valves [39]

5.3.3. Electro-Mechanical Fuelling System

The fuel system of the gas turbine was modified to allow the engine to be run either manually or via the digital control system. Components selected were to meet the specifications required for implementation of the future digital fuel control law to be developed in Phase II of the project.

The electro mechanical fuel control system was connected in parallel with the original mechanical governors. The changeover between these two systems was facilitated by three solenoid actuated changeover valves. The first of these valves directed flow from the high pressure fuel pump into either the electro-mechanical or full mechanical system. A second valve selected from which system the metered fuel would be supplied to the nozzle and the last changeover valve allowed excess fuel to be fed back to the inlet of the high pressure pump from the active system. The valves were specified to meet maximum expected pressures and flow rates in each of the fuel lines in which they were located. The electric actuators connected to these valves possessed actuation times of less than five seconds. This was deemed sufficient for the changeover procedure which was to be carried out with the engine in steady state. The housing units of the electric actuators bore a rating of IP66 for protection, admitting neither dust within the housing nor any water from high pressure water jets in any direction.

An electro-pneumatic overspeed valve that doubles as an emergency shut off valve was incorporated into the system to protect against damage to the drivetrain components as a result of excessive turbine speeds or over temperature conditions. This valve was situated in the line ahead of the fuel nozzle, thus when activated fuel to the engine was cut off directly before entering the combustion chamber. Each of the aforementioned valves was placed such that in the event of electrical failure the changeover valves would default to the mechanical fuel system and the shut off valve would cut fuel to the engine. The table below lists the specifications for each of these valves:

Table 12: Swagelok Valve Specifications [50]

Application	Part Number	Connection Size	Cv	p (bar)			90° Actuation Time	Duty Cycle
				0.68	3.4	6.8		
				Water Flow (L/min)				
Fuel Supply Selector	SS-42GX-41ACXE	¼ inch	0.35	4.1	9.0	13	2.5 s	40%
System Selector	SS-43GX-42ACXE	8 mm	0.8	9.4	21	30	4 s	30%
Emergency Shut-Off	SS-42GS4-310OE	¼ inch	0.6	7.1	15	22	Energise: 8 ms De-energise: 10 ms	

The heart of the fuel control system was the flow meter/controller and control valve combination. Careful consideration was paid to selection of these components ensuring that they would fulfil the necessary criteria for metering of the fuel. A coriolis type flow meter was elected due to its fast response time, accuracy, repeatability (0.1% of flow rate), low pressure drop and ability to measure mass flow rate directly. A Bronkhorst Cori-Flow device was used in conjuction with a Badger control valve with a TEIP11 converting the input current from the Cori-Flow to a Pneumatic output suitable for actuating the valve. The protection ratings for both devices was set as IP65, this assures no dust ingress and shielding against low pressure water jets from any direction. The Cori-Flow possessed a highly accurate Analog to Digital converter (ADC) which scales the sensor signal before filtering and linearization take place. An enhanced PID control loop within the instrument was used to control the metering valve.

The Bronkhorst instrument included a microcontroller capable of running a number of processes simultaneously. Parameters and settings could be adjusted through the digital communication line RS232 using either proprietary Bronkhorst software or LabVIEW. Measured values were output and set points were communicated to the device via the integrated analogue interface and the National Instruments Compact RIO. Firmware on the controller calculated settings for the valve actuator according to the given set points and a digital **P**ulse **W**idth **M**odulation (PWM) signal synthesised by the controller was utilised to drive the control valve. A diagram depicting the controller layout follows in Figure 39.

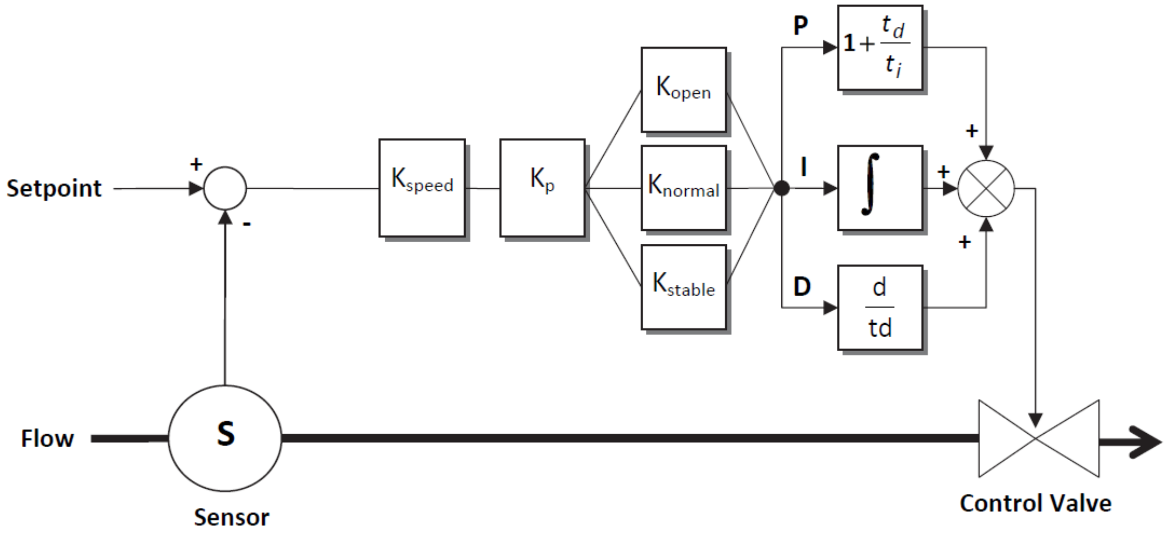


Figure 39: Basic Controller Diagram for Cori-Flow Device [51]

Alarm conditions were set for system errors and warnings as well as a maximum flow rate limit. In the event of fuel flow rate through the device exceeding the given maximum the system would revert to using a pre-set safe maximum flow rate thus preventing overspeed or over temperature conditions in the gas turbine. A delay was programmed to prevent reaction to glitches in measurement or power triggering false alarms.

5.4. Digital Systems

The digital systems of the electronic control unit for the T63 gas turbine integrate the control, monitoring and data logging tasks. This was achieved through manipulation of the actuators in response to user input and sensor data, archiving all recorded data for further analysis. Careful planning of the system architecture was central to the development of the ECU to administer these responsibilities smoothly and effectively.

5.4.1. Hardware Infrastructure

The hardware infrastucture of the digital system was laid out in a distributed heirarcal architecture as is depicted in Figure 40. This style of architecture afforded a number of advantages over a centralised control system. At the highest level two computer systems were set up to perform monitoring and logging functions and provide a means of user interface. This afforded the advantage of system redundancy with safety mechanisms built into both systems and duplicate data being stored. Full automation was achievable via each of the host computers using either the ETA or LabVIEW software packages (refer to Section 5.4.4 for more information). These two separate systems were designed such that certain tasks were distributed between them, this decreased processor load on both systems. The two computers were networked using a hub and ethernet connections, a software package called Input Director was installed on both machines. This made it possible to access all management applications and data logged from a single location using only a single shared mouse and keyboard.

The second level was concerned with system control and acquisition of data. The Schenck X-act controller and NI CompactRIO, control the dynamometer and T63 gas turbine with its subsystems respectively. Physical variables were acquired via the various sensors and were passed to the Allen Bradley Programmable Logic Controller, the CompactRIO and the Schenck controller. These sensors and the actuators that execute the commands of the control level form the final field level. The rates of data acquisition for each of the aforementioned devices were set to a frequency of 10Hz. Higher sampling rates were possible however one must note that there are resource costs associated with the increased amount of data to be processed and recorded. The 10 Hz sampling rate was selected as an improvement on the previously employed 5Hz frequency to give better achievable control quality without stressing resource capabilities. This rate of acquisition was based on a spool time constant for the T63 of above 0.4 seconds [21]. The Nyquist Sampling Theory discussed in Section 2.5.5 states that the rate at which samples are collected should be at least double the frequency of the input signal and any disturbances that might affect it. The bar is thus set at a minimum of 5Hz however the rule of thumb applied in industry suggests a higher value is optimal. Thus the sampling rate of 10Hz was required to reduce possible aliasing effects mentioned in Section 2.5.5.

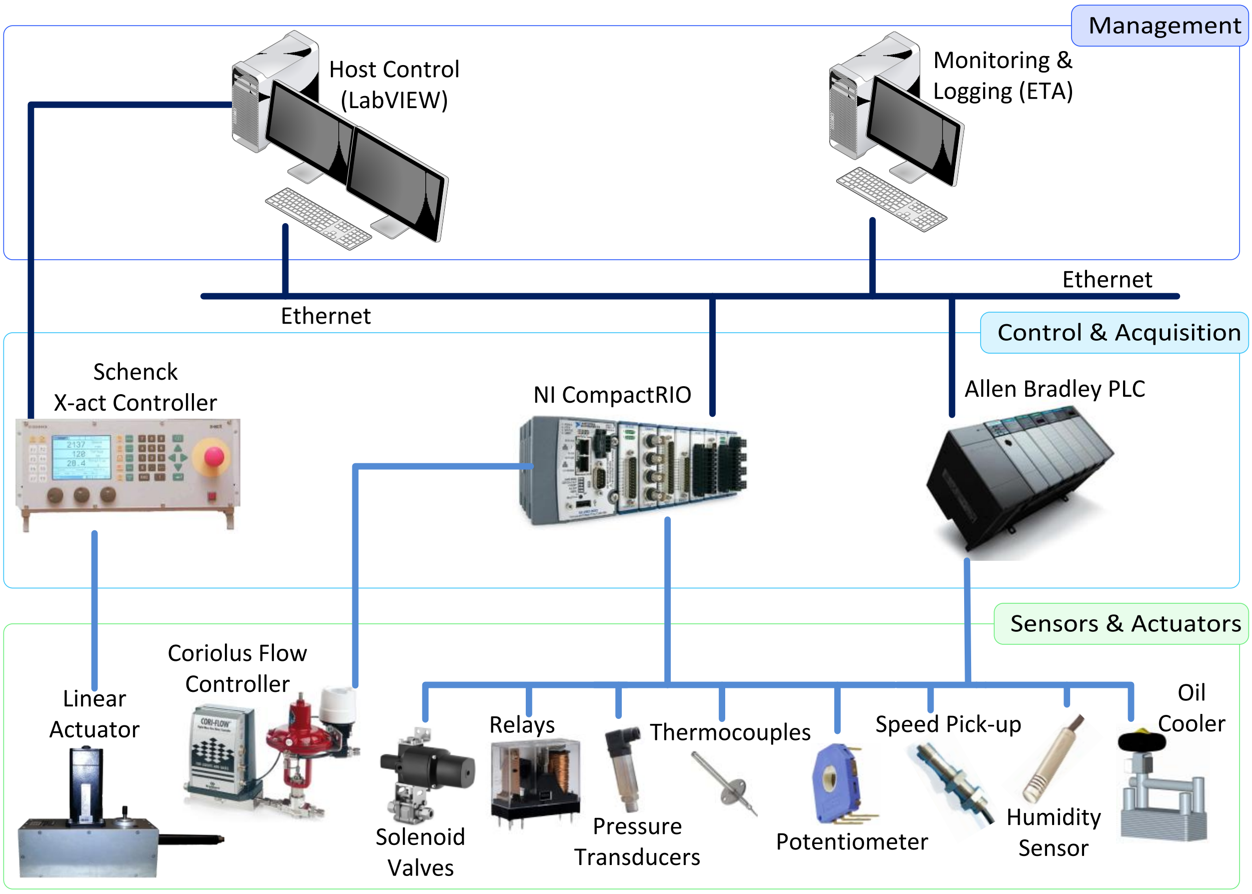


Figure 40: Hardware architecture of digital system

5.4.2. Software Architecture

The system architecture, shown in Figure 40 and Figure 41, provides a basic overview of the system and includes all processes and communication paths. Establishing a layout for the architecture of the software at an early stage in the development process allows one to keep track of all of the software components and communication paths between them. Three top-level LabVIEW programs known as **V**irtual **I**nstruments (VI's) were created for each of the three targets: the host PC and the **F**ield **P**rogrammable **G**ate **A**rray (FPGA) and real time processor of the NI CompactRIO. These VI's executed asynchronously to monitor and control gas turbine operations as well as to facilitate communication of the user's commands. Figure 41 shows the software architecture employed, the two devices on which the VI's are loaded are shown in blue while each of the VI's is indicated in green. Each VI executes a number of tasks that are broken down into several independent processes or loops connected by communication paths along which data is transmitted. The tasks were split into a number of individual processes to maintain a more scalable and modular program. Single processes can thus be created or redesigned at a later stage without impacting the other processes. Sub VI's were employed within the main VI's to conduct sub routines. This method of programming kept the code neat and modular.

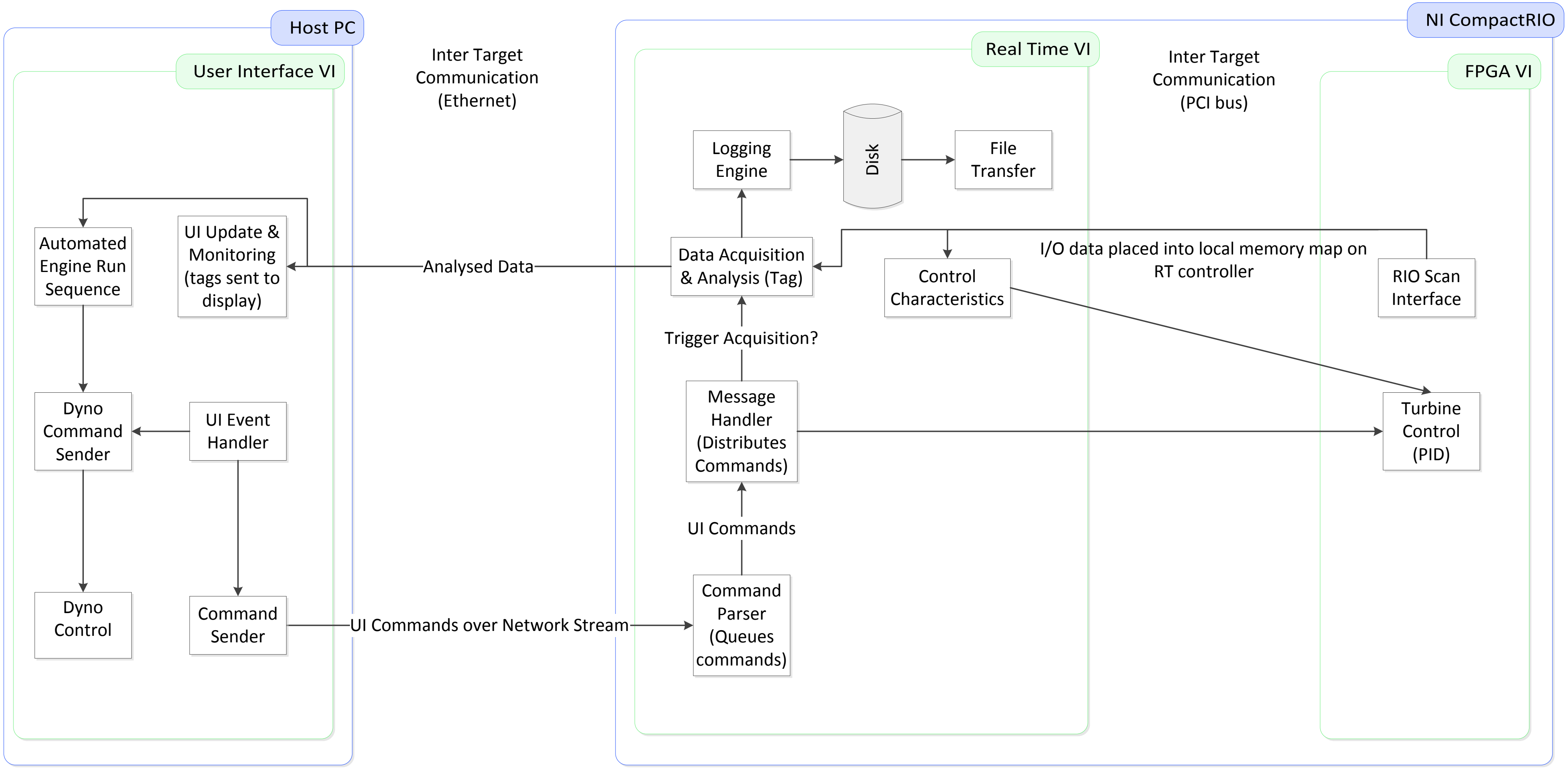


Figure 41: Software Architecture

Command-based communication and current values (tags) were the two data communication models utilised between both processes and hardware targets of the system. The command-based communication occurs when triggered by a specific event such as a user interaction with the system. Queues and real time first–in-first-out (FIFO) buffers were employed to ensure delivery of these messages at low latency such that the delay between input command and output response was unnoticeable to the operator. Tags were used to transmit the current values of the various process variables, such as set points to the associated processes. A Current Value Table formed a shared data repository between the applications for a large number of I/O variables. Single-Process Shared Variables with a single element real time FIFO buffer enabled were put to use transferring time critical data between loops and targets.

The VI on the host PC provided an event-based graphic user interface that allowed the operator to interact with the embedded system of the CompactRIO. Dynamometer communications were all initiated by the user over the host computer's **P**eripheral **C**omponent **I**nterconnect (PCI) **C**ontroller **A**rea **N**etwork (CAN) card and were therefore also handled by this VI. The real time operating system executed the data logging process and set all the turbine control characteristics. The FPGA acquired data and capacity was retained for future use to perform low-level control in the form of the fuel control law. The FPGA module of the CompactRIO was programmed in hybrid mode, utilizing both the Scan Interface and LabVIEW FPGA Interface. The graph shown in Figure 42 was used to decide the mode in which each of the input/output modules should be programmed.

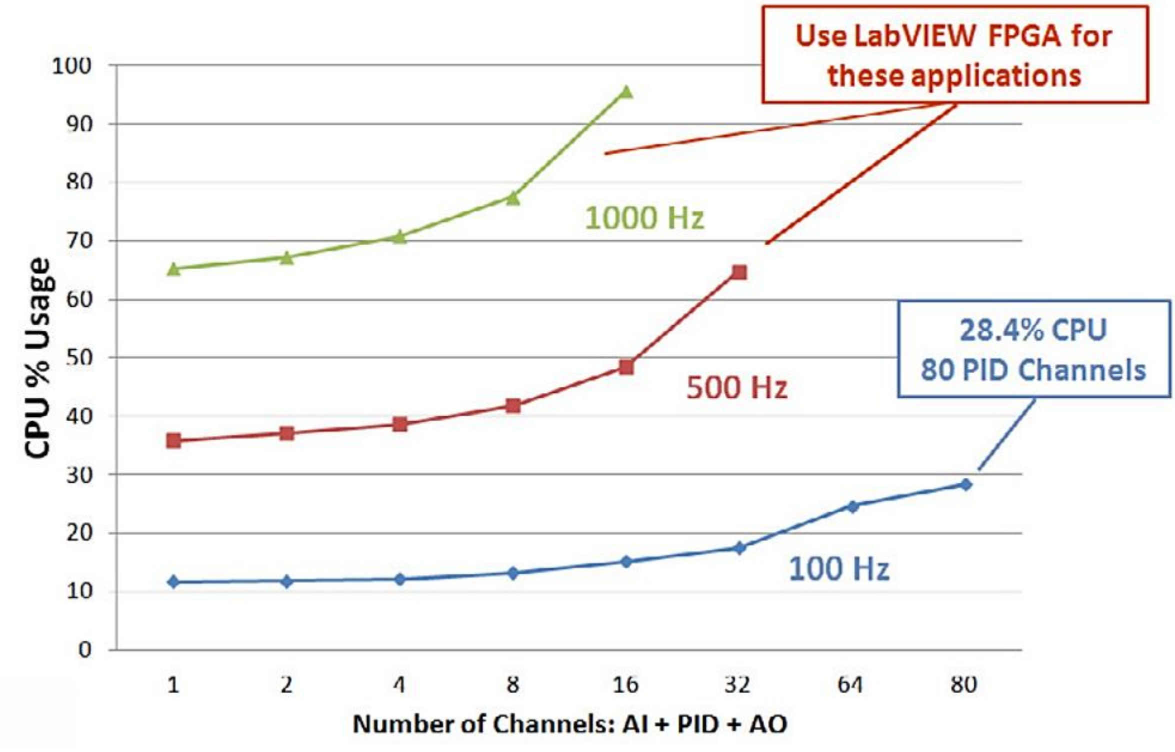


Figure 42: Performance comparison between Scan Interface and FPGA Interface modes [52]

The FPGA interface was reserved for use with the NI modules directly involved with future implementation of the fuel control law of the gas turbine. The inputs and outputs of the modules left in Scan mode were periodically scanned and placed in a memory map. The current values stored in this map could then be read from at will in any of the project VI's. Scan Interface mode was used for the relatively low speed, high channel count processes associated with data logging and GUI updates. Scan Interface mode permitted ease of programming and improved diagnostics and debugging. This coupled with the maximised performance and reliability of FPGA mode enabling high speed analysis meant running in hybrid mode was advantageous. A disadvantage to running in hybrid mode was that the time taken to compile code for the FPGA was increased as both the Scan Interface and FPGA code had to be combined into a single bit file.

Inside the VI's timed loops were used to set period and priority of time critical loops such as those used for closed loop control and for the FPGA and RIO Scan Interface. These loops would then run at the given rate without interruption and with minimal jitter. For the duration of the period that these loops run they monopolise one core of the system on which they are executing therefore care was taken to ensure other tasks within the application would have sufficient time to run in the interim periods.

Once the structure of the code had been laid out it was possible to progress to the construction of each of the main VI's. The sections that follow describe in detail the main processes of which the main VI's were composed.

5.4.3. Dynamometer Control

The output shaft of the T63 gas turbine installed in the SAFL test cell had been connected to a Schenck W3S 480 eddy current dynamometer. Load control of the engine was achieved via the dynamometer's electronic controller which delivered a fast torque load response.

The original test cell set up gave the operator two options for communicating set points and control modes to the dynamometer's X-act controller. The first of these options was a manual adjustment using the controller's physical front panel. Alternatively the ETA software package had been configured such that communication with the dynamometer controller was possible utilising controls on the PC user interface. The ETA source code was inaccessible however so no changes could be made to these programs that were not already built in.

At the onset of the project a number of user requirements were laid out, one such requirement specified that the electronic controller designed for use on the T63 should enable automatic start-up of the engine. To facilitate the inclusion of this function on the device it was necessary to obtain control of the dynamometer via communications from the digital controller created in LabVIEW. Section 1 of Appendix B details this process.

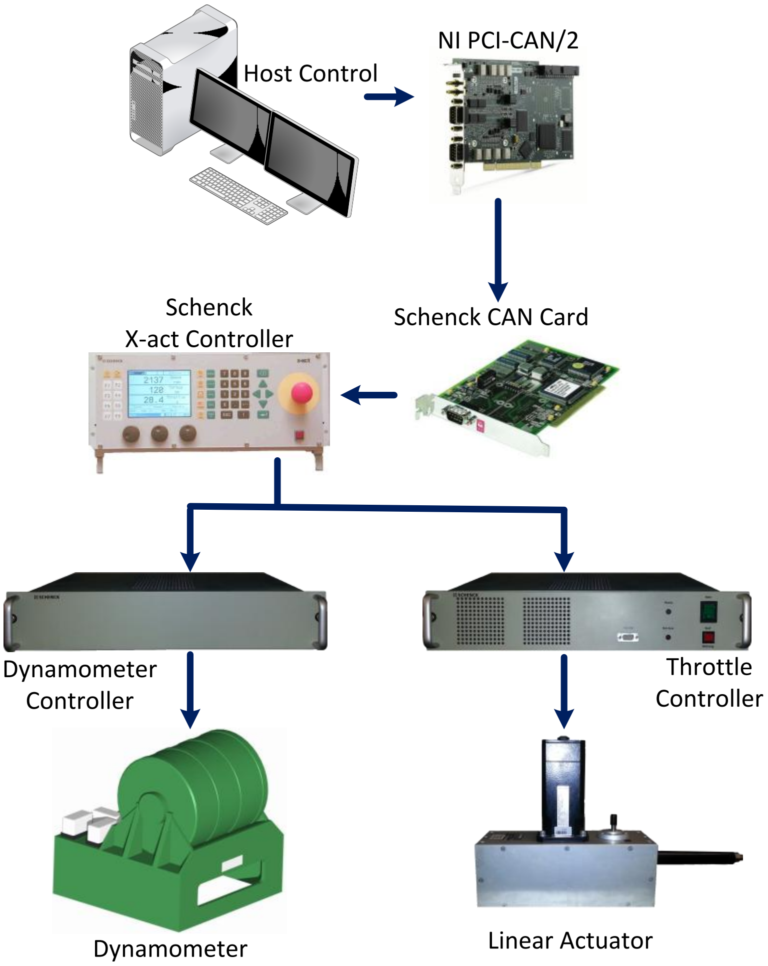


Figure 43: Dynamometer & throttle control layout

Communication with the X-act controller was facilitated by the use of CAN cards installed in both the host and target devices. Communication between the host and target was achieved by transmission of messages in the form of frames. Standard frame format utilising an 11 bit identifier was employed to send and receive data to and from the X-act controller. The dynamometer's X-act controller proffered two options for communication of data, known as online and offline communications. Online communications could be configured to transmit at a rate of up to a max of 100 Hz. Synchronous transmissions of the configured type then took place periodically. Offline communications involved a command or request being sent from the host to the X-act, which then responded accordingly.

Communications code was written and tested separately in both the online and offline formats. An iterative design philosophy was employed such that the initial goal was to obtain a working prototype of each piece of code that could then be refined based on results from testing and analysis. Thus the final code utilised in the ECU amalgamated both the online and offline communications processes into the dynamometer driver. This program ran smoothly - processing, displaying and logging data at an optimum rate. The dynamometer driver was structured as three distinct state machines, pictured in Figure 44, Figure 45 and Figure 46. Further detail about these state machines and the code development is contained in Appendix B: Section 1.3.

A sequence of commands was built into the dynamometer control code to communicate with the Schenck X-act controller's signal generator. This feature was not possible with the ETA software package but was seen as a necessary addition to the LabVIEW implementation as it was required to enable frequency testing of the gas turbine, linear actuator and dynamometer. As mentioned in Section 2.5.6, sinusoidal signals needed to be generated as inputs to these systems such that system identification could be carried out during the control law formulation planned for future implementation on the engine.

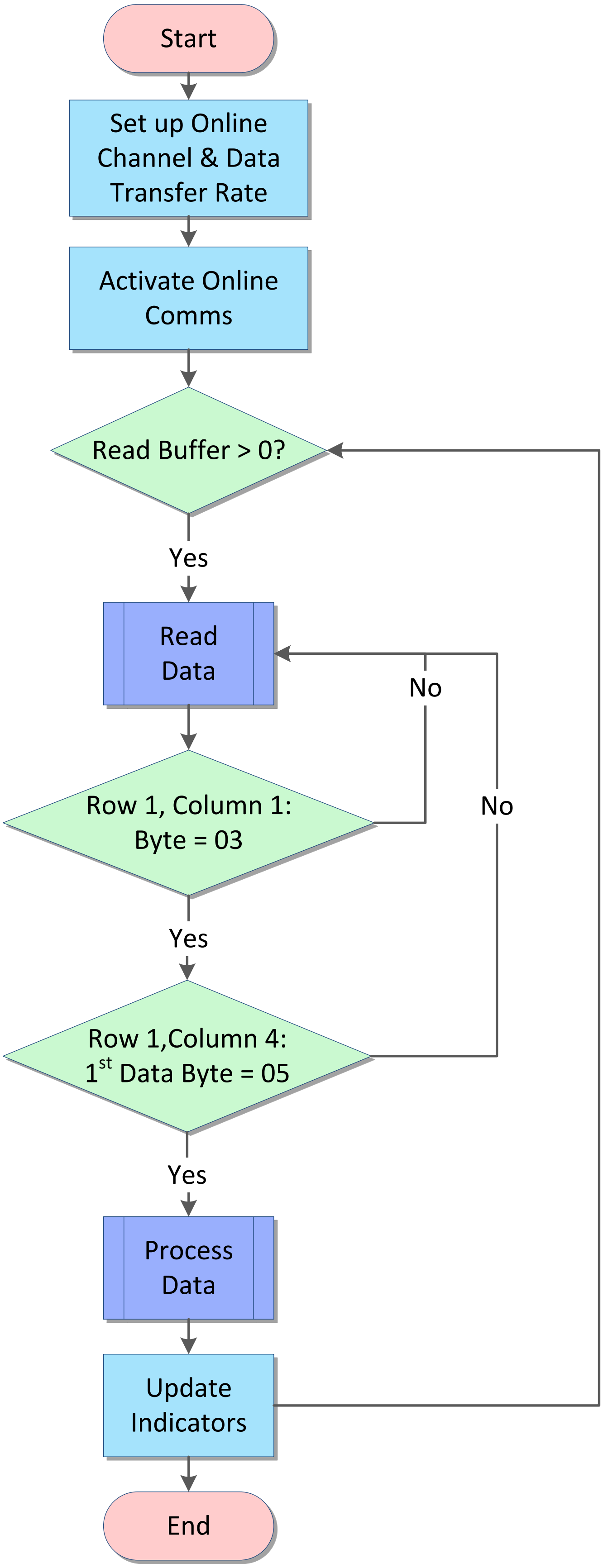


Figure 44: Flow diagram for online data read from dynamometer

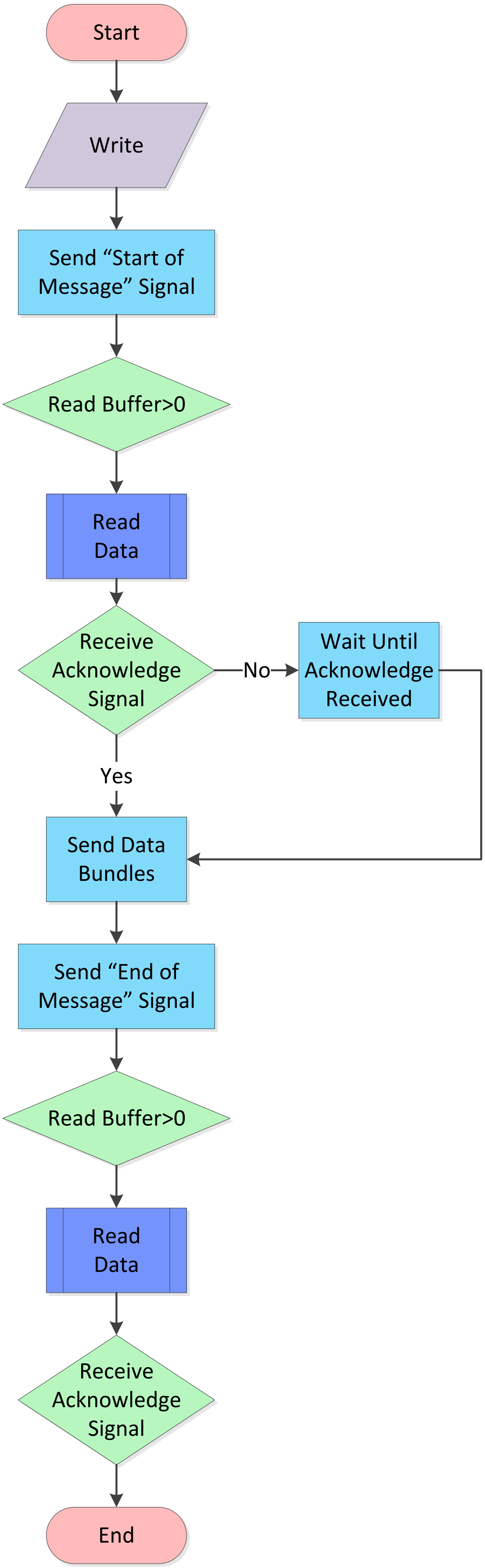


Figure 45: Flow diagram for offline data transmission to dynamometer

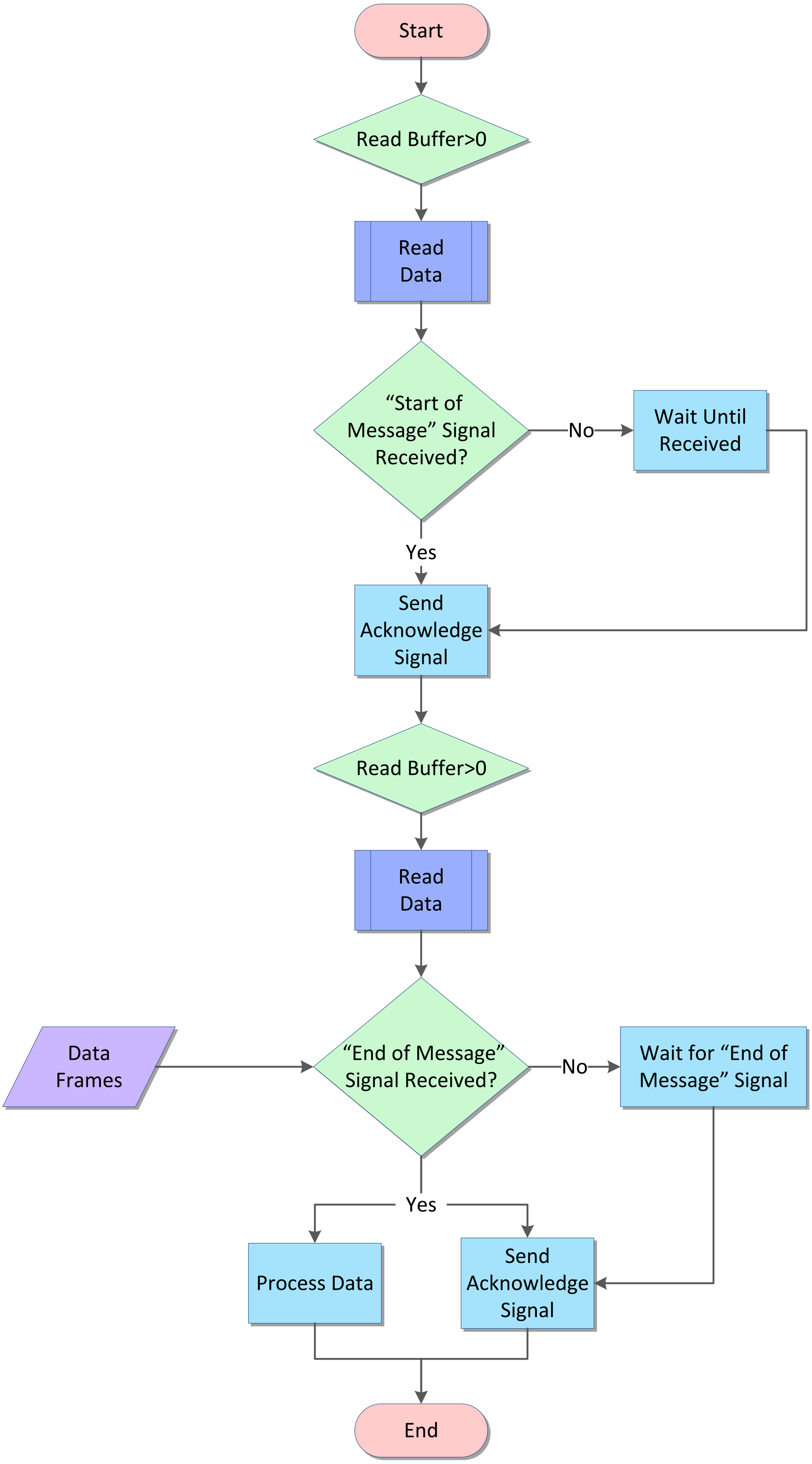
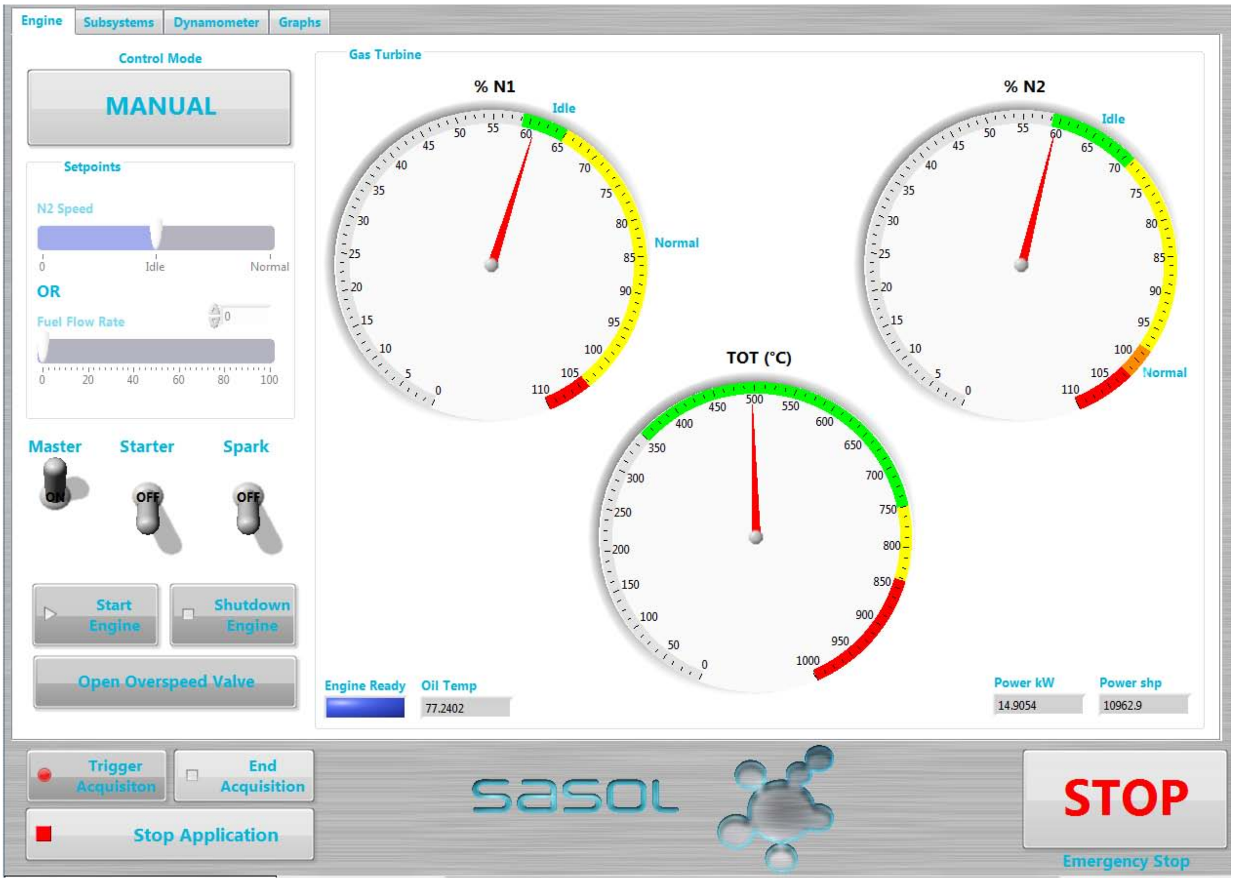


Figure 46: Flow diagram for offline data read from dynamometer

5.4.4. Turbine Control

ETA software was used to monitor and log data going to and from the gas turbine via an Allen Bradley PLC. The system is pictured on the far right of Figure 40 of Section 5.4.1. Gas turbine operations were initially automated using ETA, configured to communicate with the X-act controller, allowing the optimum sequence and timing for automation to be determined. Complete system control was not possible through ETA due to restrictions in code accessibility thus LabVIEW was programmed to take over control duties. ETA was maintained as a redundant system, decreasing processor load on the LabVIEW host PC by monitoring subsystems such as the oil and water supply.

The LabVIEW code was composed to allow user interaction with the system and monitor engine and subsystem operations. A graphic user interface was provided to permit the user to manipulate parameters such as the output speed, dynamometer torque and fuel flow to the engine. Gas turbine and subsystem variables were displayed as on screen indicators as shown in Figure 47. In the case of any operating limits being approached a visual warning was the first indicator to be given. If no corrective action was taken by the user the programme was set to automatically decrease fuel to the engine by bringing down the throttle set point.



Control Mode MANUAL

Oil Temp 77.2402

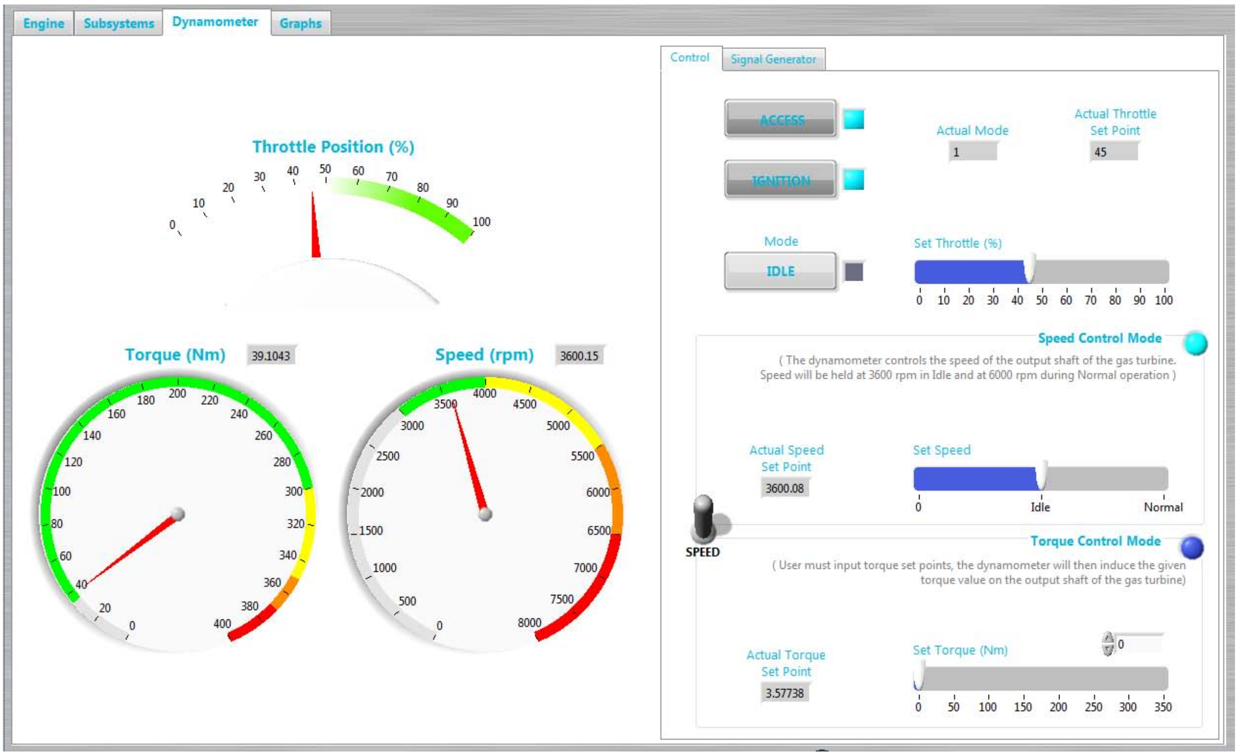
Power kW 14.9054

Power shp 10962.9

Figure 47: Main engine tab LabVIEW user interface

The dynamometer could be run in either torque/speed control mode or in speed/throttle mode with all dynamometer and throttle settings accessible via the LabVIEW user interface. The controls and indicators of the dynamometer tab of this user interface are pictured in Figure

48. Automated sequences could be activated that controlled the gas turbine subsystems and dynamometer to perform the start-up and shut down procedures. All necessary checks and safety procedures were included in these sub routines.



Torque (Nm) 39.1043

Speed (rpm) 3600.15

Actual Mode 1

Actual Throttle Set Point 45

(The dynamometer controls the speed of the output shaft of the gas turbine. Speed will be held at 3600 rpm in Idle and at 6000 rpm during Normal operation)

Actual Speed Set Point 3600.08

(User must input torque set points, the dynamometer will then induce the given torque value on the output shaft of the gas turbine)

Set Torque (Nm) 0

Actual Torque Set Point 3.57738

Figure 48: Dynamometer tab of LabVIEW user interface

Each of the two software systems was set up with an independent data logging system. ETA handled data input from a number of fluid supply systems, sensors and from the gas turbine. LabVIEW was committed to archiving the gas turbine spool speeds, turbine outlet temperature and exhaust temperature, control relevant fluid supply information and all data acquired from the dynamometer.

Inter-target communications allowed data to be sent from the LabVIEW user interface on the host computer to the real time processor of the CompactRIO. Queued elements were transmitted via a FIFO buffer and network stream from the host VI to the CompactRIO. This provided a lossless means of one-way communication with high throughput capabilities.

With inter target communications in place, the software development stage could be brought to a close. The aforementioned end product of this project has been described in brief with further detail and explanations for component selection and software augmentation decisions covered in Appendix B. The evolution of the electronic control unit of the gas turbine involved a great deal of iterative evaluation. A portion of these processes are chronicled in the ensuing chapter.

6. Testing

The development process of any project requires that a number of test procedures are undertaken to determine the functionality of the system both before and after fabrication. The design process could only be concluded once successful implementation of the device had been achieved. The work recounted in this chapter describes improvements made to the original system as well as results of the various test procedures carried out on the ECU.

6.1. Commissioning of Original System

Before baseline testing could commence it was necessary to ensure the original system and subsystems were in full working order. During the initial commissioning tests a number of issues were encountered that needed to be addressed before further progress could be made.

6.1.1. Engine Overspeed

The first of these issues was a dynamometer water sensor malfunction that led to the dynamometer rapidly reducing load mid run. If the engine was run under load and at full speed the sudden loss of load could lead to engine overspeed. Thus this problem needed to be resolved before further runs could be made. The solution implemented was the installation of a solenoid valve in the gas turbine's P_y signal line that ran between the N_G and N_P governors. The solenoid valve, when opened, bleeds air from the signal line to atmosphere and immediately drops the engine speed to low levels as can be seen in Figure 49 and Figure 50 which depict engine response to a bleed at both loaded and idle conditions. Figure 51 shows a bleed in idle mode followed by the closing of the bleed valve and the engines return to normal idle operation. The valve is in a normally open position when not under power allowing it to perform a secondary function as a safety device in the case of a power failure.

The cause of the dynamometer trip switch being activated traced to the dynamometer water flow sensors. An investigation into the previous history of the dynamometer revealed that this was a recurring issue, solved in the past by cleaning each of the sensors of any build up that may have accrued. Hence the dynamometer water sensors need to be cleaned on a regular basis as a part of a routine maintenance procedure. The flow sensors were bridged out of the circuit as an alternative to this cleaning procedure. A flow switch was installed in the water line providing water to the dynamometer; this flow switch was wired to the Allen- Bradley PLC. Using the ETA software a warning signal is produced that has been coded to open the P_y valve before a dynamometer trips, thereby preventing engine overspeed. Ultimately the addition of the flow switch and disconnection of the dynamometer sensors allowed for a more controlled shut-down by the PLC in the event of insufficient water supply to the dynamometer.

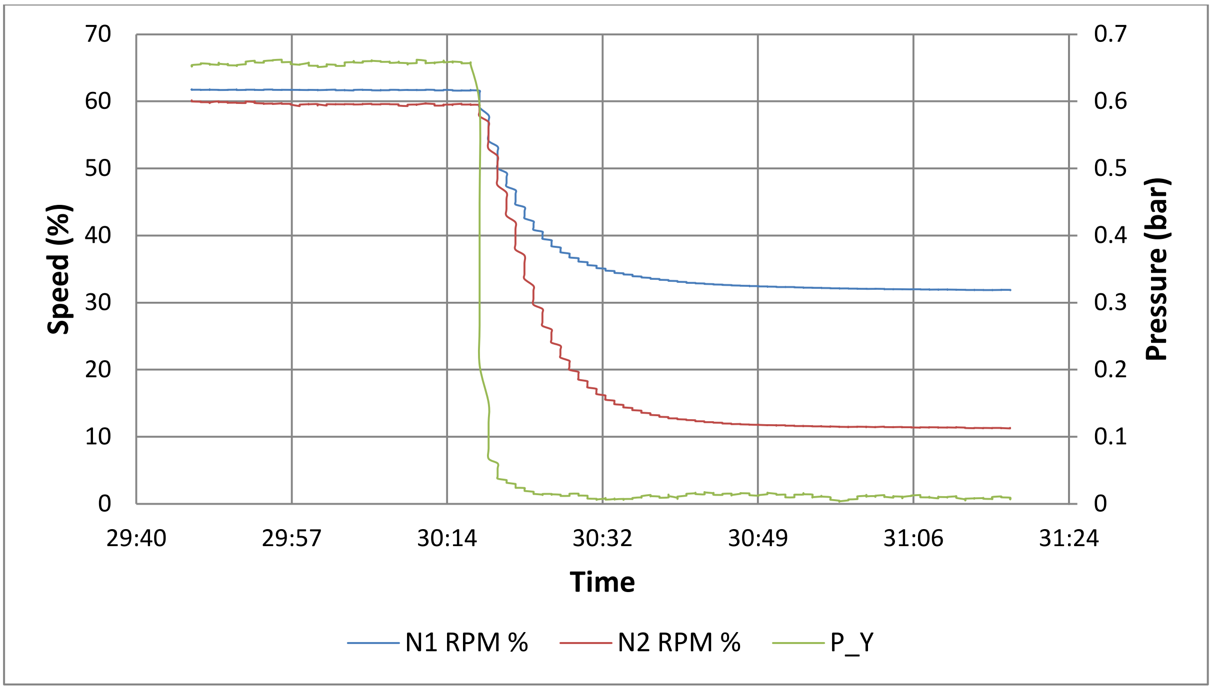


Figure 49: Air bleed of P_Y signal line with engine initially in idle conditions

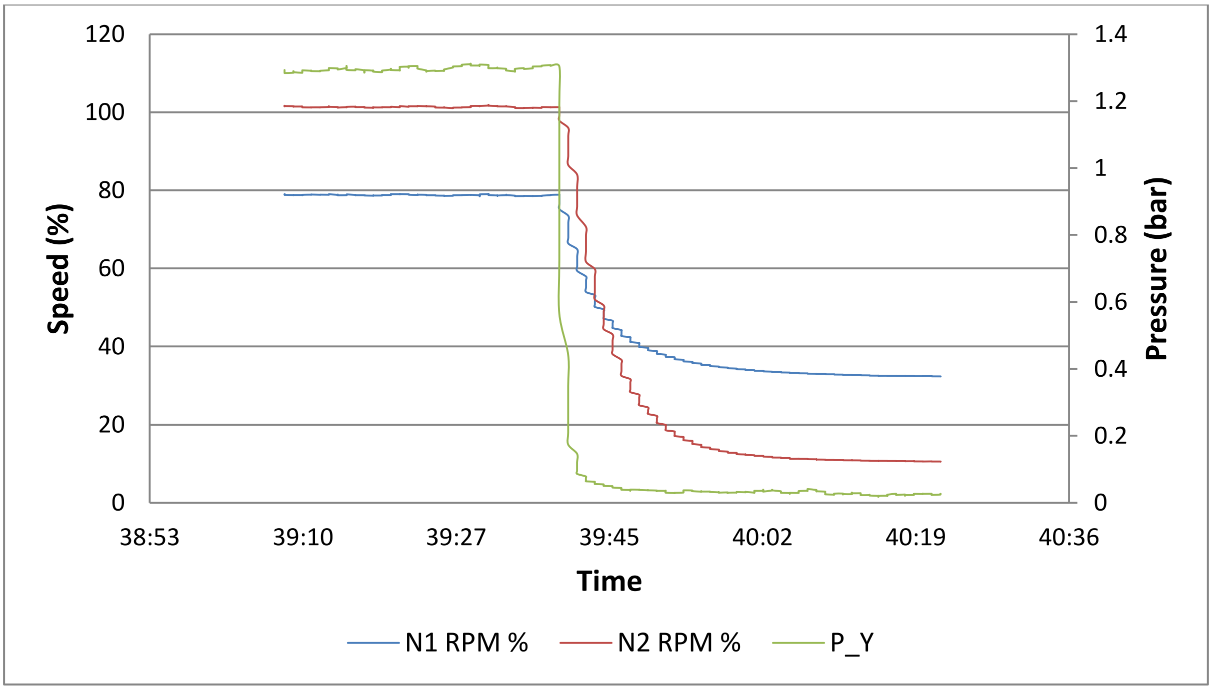


Figure 50: P_Y air bleed with engine initially in full speed condition under load = 60Nm

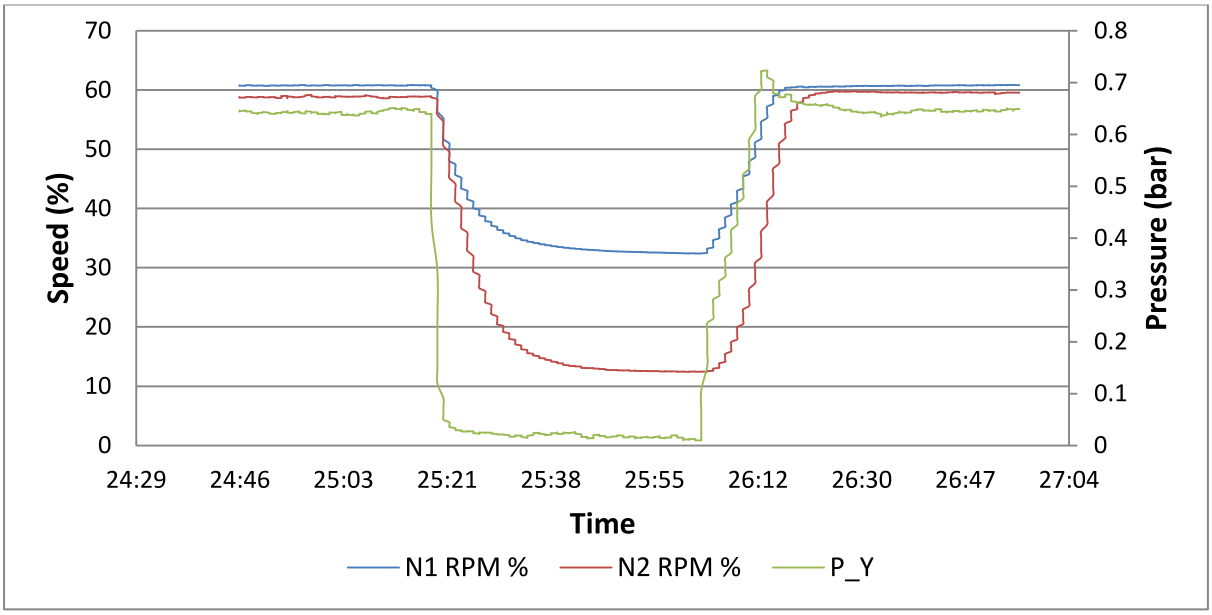


Figure 51: P_Y air bleed from idle, closing of bleed valve and subsequent engine recovery

6.1.2. Engine Surge

The second condition that required rectification was the presence of engine surge conditions when running the engine at full speed (N_P at 100%).

The T63-A-700 gas turbine was designed for service mounted within the OH-58 helicopter. The setting of the power turbine governor is, in this case, changed with adjustments to the blade pitch of the main rotor system. This change in the angle of attack of the rotor blades is what affects the aircraft speed and does not require an increase in speed from the power turbine but does increase the load applied to this turbine. Therefore the power turbine speed remains constant at approximately 35,000 RPM throughout operation while the gas generator speed varies in order to facilitate this. This means that the speed of the output shaft connected to the main rotor assembly also remains constant at 6000 RPM.

In the test cell set up at the Sasol Advanced Fuels Laboratory the output shaft of the T63 is directly connected to that of a Schenck eddy current dynamometer, which controls the torque applied to the output shaft.

The main rotor gearbox of the helicopter has a total reduction ratio of 17.44: 1 [53] and the rotational inertia of the main rotor system of 1822 $kg.m^2$ [54]. This means that the inertia caused by the load normally experienced by the T63 can be calculated by the following equation:

$$\text{Reflected Load Inertia} = \frac{\text{Load Inertia}}{\text{Reducer Ratio}^2} + \text{Reducer Inertia}$$

$$= \frac{1822}{(17.44)^2} +$$

$$= 5.99\ kg.m^2$$

The helicopter's main rotor system possesses a rotational inertia of 5.99 $kg.m^2$ while that of the eddy current dynamometer is a fraction of this, being only $0.42 kg.m^2$. The result of the decreased rotational inertia experienced is the engine speed oscillations at ~100% N_2 These oscillations are due to the fuelling schedule accounting for a higher inertia system that requires larger fuelling changes in order to overcome speed variations. The controller therefore injects too much fuel and overshoots the desired set point with the variation in speed, for the same reason it then overcorrects once more by overly decreasing the fuel supply and the cycle perpetuates.

The surge condition had been present since the initial installation of the T63 and previously was addressed by the introduction of a manually operated bleed valve. The valve bleeds air from the regulated pressure (P_R) signal line of the power turbine governor. Opening this valve bled air from the P_R signal line to the atmosphere thereby damping the effect of the governors by decreasing the scale of the P_R-P_G feedback with respect to speed. [5]

While the addition of this bleed valve led to improved system operation it did not eradicate the oscillations completely and under certain conditions the system could become unstable. The following options were considered to correct this issue:

- Incorporate a flywheel to increase rotational inertia of the system
- Improve the dynamometer control strategy
- Alter the engine fuel control unit.

A thorough literature search yielded a fourth option:

The Naval Postgraduate School situated in Monterey, California previously installed a similar test cell at their facilities in which they utilised a T63-A-700 gas turbine. The operating procedure which they followed differed from that laid out in the Rolls–Royce 250–C18 Series Operation and Maintenance manual in that the N_P lever of their test rig has been permanently locked into the maximum position permitting full control of the power turbine by their water brake dynamometer. The N_P lever controls the sensitivity of the fuel controller with respect to power turbine speed. When set in the maximum position the power turbine was able to reach the maximum RPM of 36,729 and the fuel controller was least sensitive to changes in power turbine speed. The dynamometer could thus maintain torque control of the power turbine by varying its speed without creating adverse reactions from the fuel controller. [55], [56].

An experimental test run was carried out in which this operating procedure was attempted. Running the gas turbine under these conditions produced favourable results with no engine speed oscillations displayed under all running conditions. Thus the decision was made to utilise this operating procedure for all further testing. The revised document detailing standard operating procedures for manual operation on the T63 gas turbine can be found on the accompanying disk. The graphs below depict engine speeds for the following three cases:

- Operation with no system modifications (Figure 52)
- Operation with the inclusion of a controlled P_r bleed (Figure 53)

- Operation with the N_P lever in the fully advanced position (Figure 54)

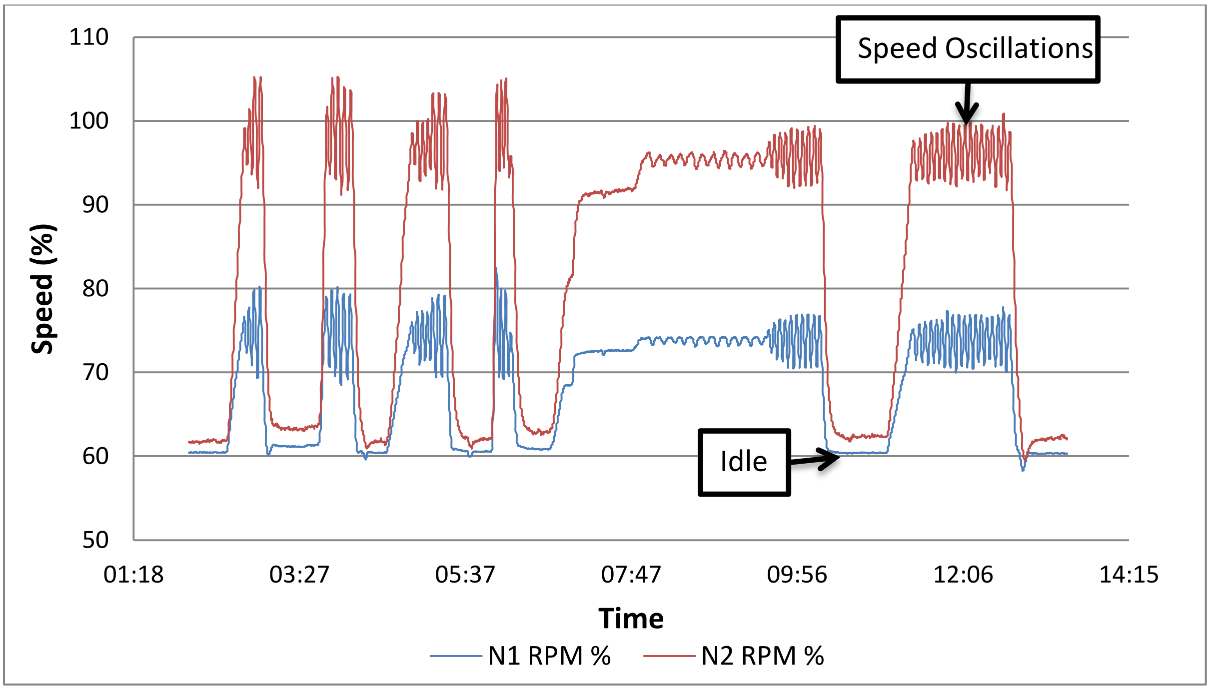


Figure 52: Trace showing turbine speeds over time for unaltered system

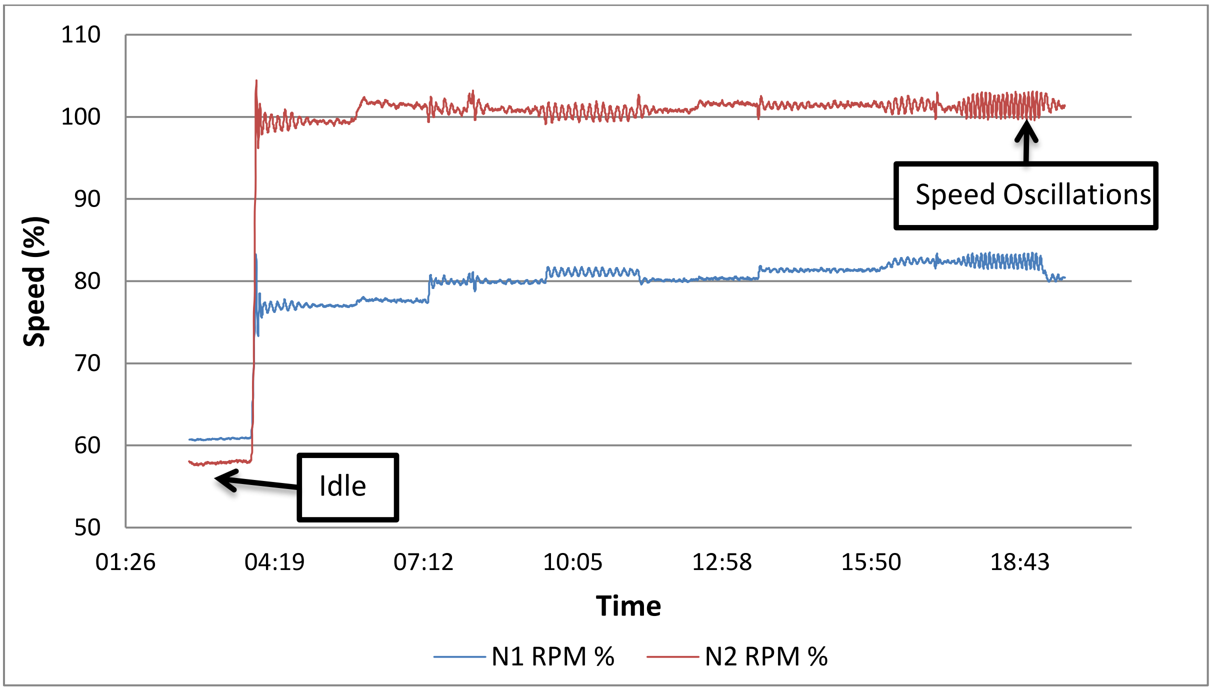


Figure 53: Effect of P_R bleed valve on turbine speeds

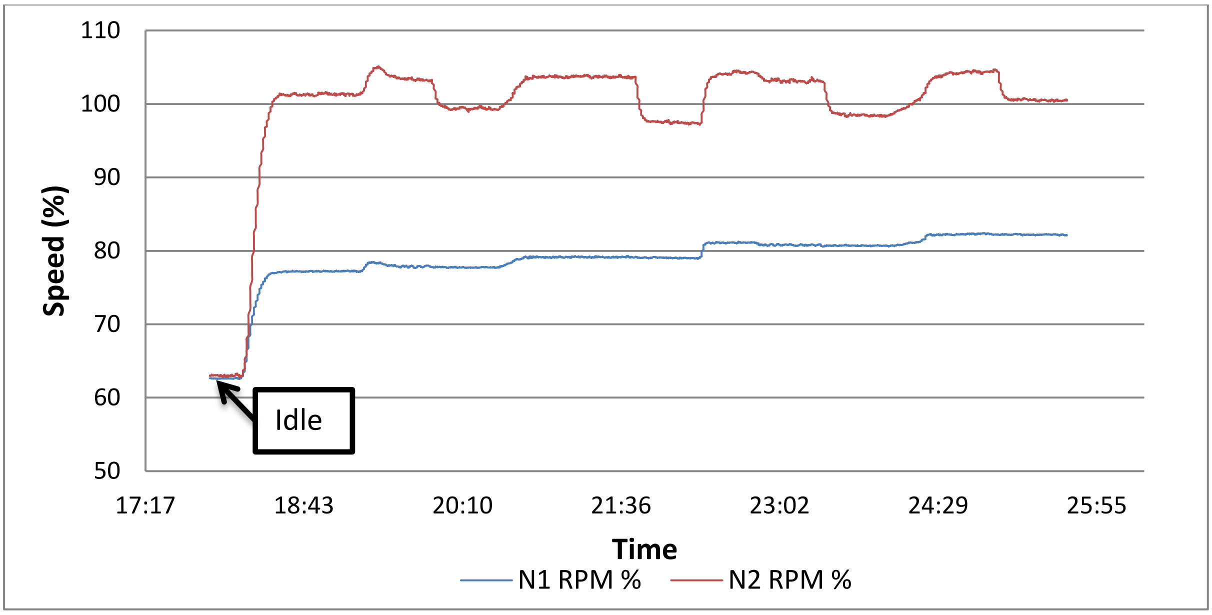


Figure 54: Turbine speeds with N_P lever fully advanced & trimming with N_G lever

6.1.3. Oil Cooler

Once stable operation could be achieved on a consistent basis, baseline testing was carried out with the gas turbine under a large range of different torque values. Operating under relatively high torque and at full speed, it was discovered that the oil cooling system could not maintain a given set point (Figure 55). Engine and PTO oil temperature must be maintained below 107°C to ensure correct engine operation. A strategy was followed to avert this effect in all proceeding tests whereby torque was maintained below 150Nm when running the dynamometer in torque mode and below 180Nm when run in speed control mode (see section 6.2.1).

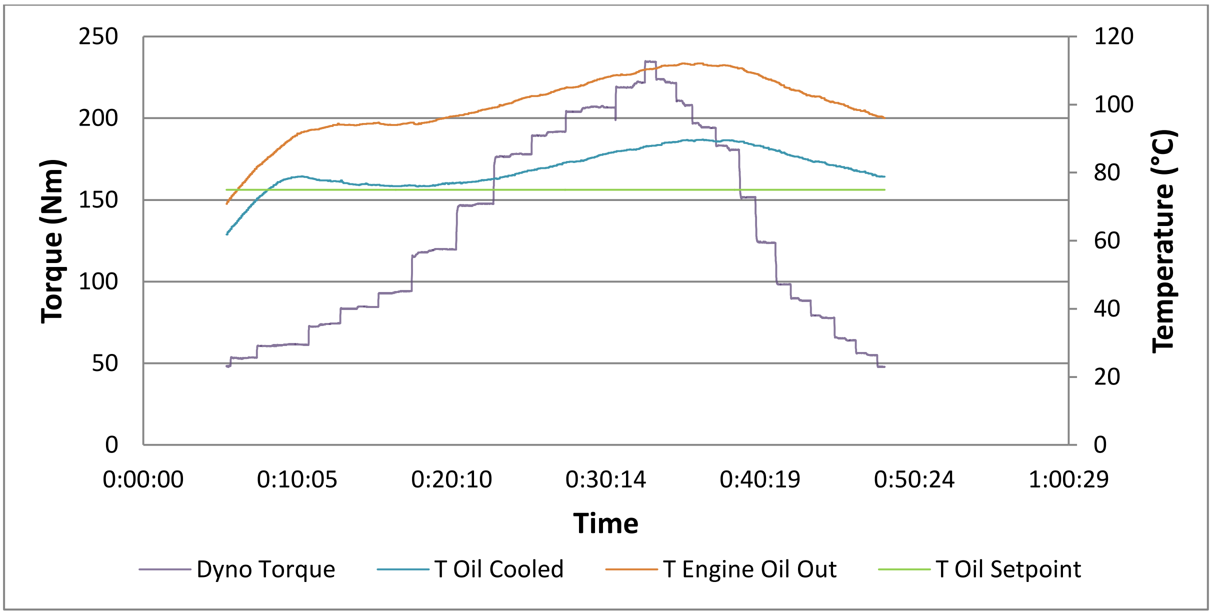


Figure 55: Engine oil temperature changes at inlet and outlet with torque steps

6.2. Commissioning of the Developed System

An incremental design philosophy was adhered to throughout the testing phase. Tests began at the most simple level to determine individual parameter ranges and were gradually broadened to include interactions between parameters and finally the response of the system as a whole.

6.2.1. Torque and Speed Control Mode Tests

The gas turbine had originally been operated with the dynamometer in torque control mode, as previously discussed in Section 5.4.4. This approach permitted the input of a torque set point, the dynamometer would then enforce resistance on the output shaft of the engine equivalent to the given torque value. Running the engine with the dynamometer in this mode was a demanding challenge requiring that the operator adjust the fuel flow rate and hence the N_G speed up and down with every alteration in torque. Only small steps in the torque value could be input such that N2 speed could be held within the allowable range. The data recorded during one of these runs appears in Figure 56. The trace shows a number of torque step inputs, throttle was adjusted accordingly to maintain N2 speed.

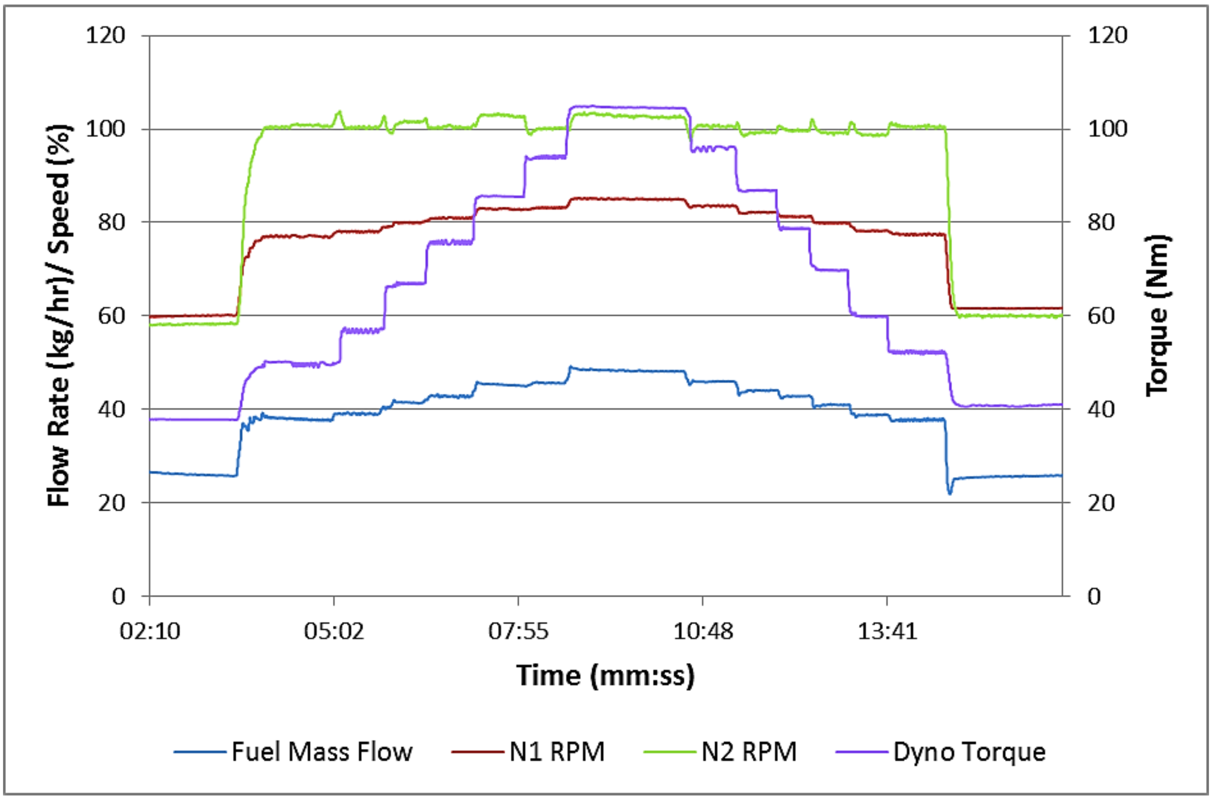


Figure 56: Step inputs to engine with dynamometer run in torque control mode

A test run was carried out to determine the viability of operating the dynamometer in throttle/speed control mode. In this mode the dynamometer maintained the gas turbine output shaft speed at a set point by automatically adjusting the load applied. Data from this test is presented in Figure 57. A notable observation was that speed of the N2 turbine was held stable at 99%. In this mode it was possible to attain greater step sizes between torque values however care should be taken not to overload the engine.

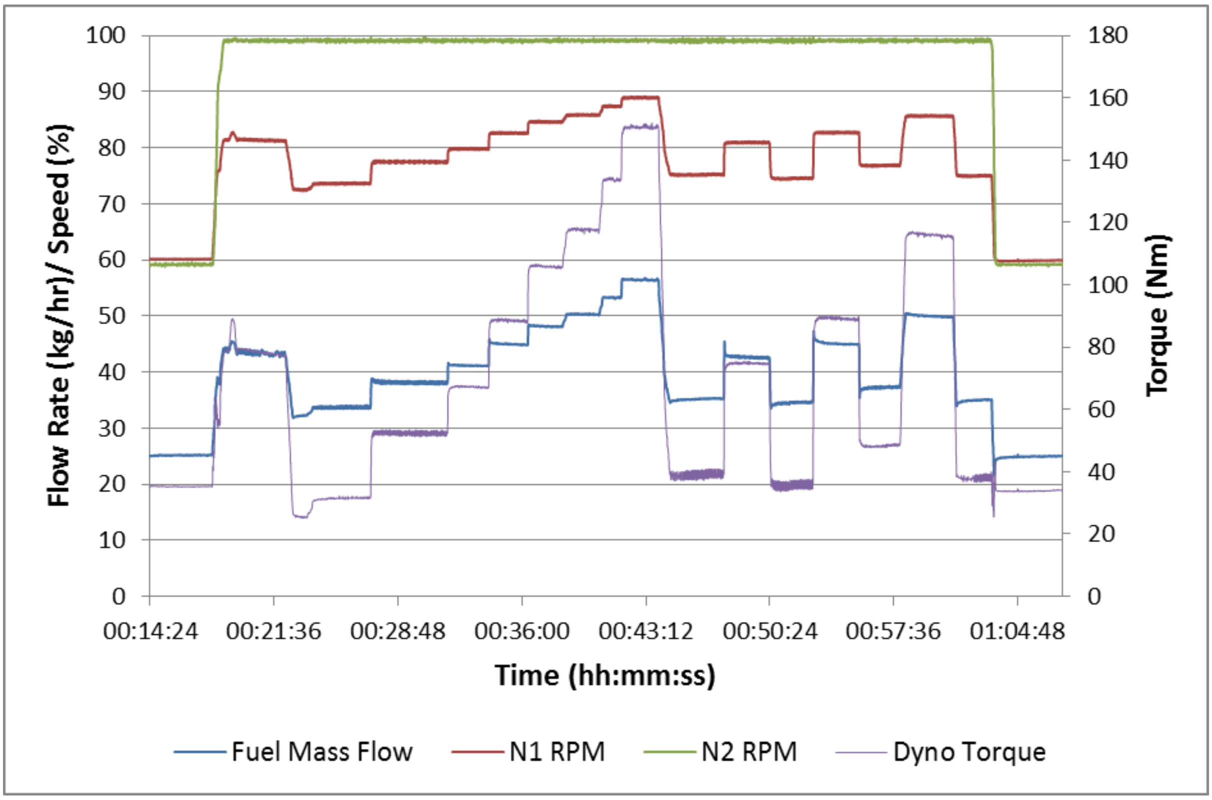


Figure 57: Step inputs to engine with dynamometer run in speed control mode

A further observation noted while testing in speed control mode were the cooler oil temperatures at higher torque conditions. In this mode a maximum torque value of 180Nm could be attained whilst maintaining the oil temperature within an acceptable range. When operating in torque control mode the highest torque set point achievable with similar oil temperatures was 150 Nm. This suggests that the engine performance is optimised when running in speed control mode. The improved operating efficiency of the engine when run under speed control mode can be attributed to the dynamometer automatically managing the engine's output accurately and in a stable region at all times.

6.2.2. Manual vs. Electronic Throttle Control

In the original set up the T63 governor throttle was positioned manually by the operator, using a lever and mechanical cable combination. Electronic throttle actuation was implemented to improve accuracy and enable automated test cycles. Figure 58 depicts the feedback information from the potentiometer connected to the throttle lever. From this graph it is apparent that the actuation speed of the throttle positioner decreases so as not to overshoot the point of flight idle. On return to ground idle the operator first fell short of the mark then overcorrected resulting in the requirement for a third amendment to attain the correct position. Figure 59 shows similar data from a second run where the mechanical throttle positioning system was employed.

On the contrary the positioning of the electronic actuator is accurate and reliable. The flight idle and ground idle settings were attained at a quicker rate with utilisation of this device. Similar rates of motion were achieved by the device over all transition periods and in both test runs. Evidence of this can be seen in both Figure 60 and Figure 61.

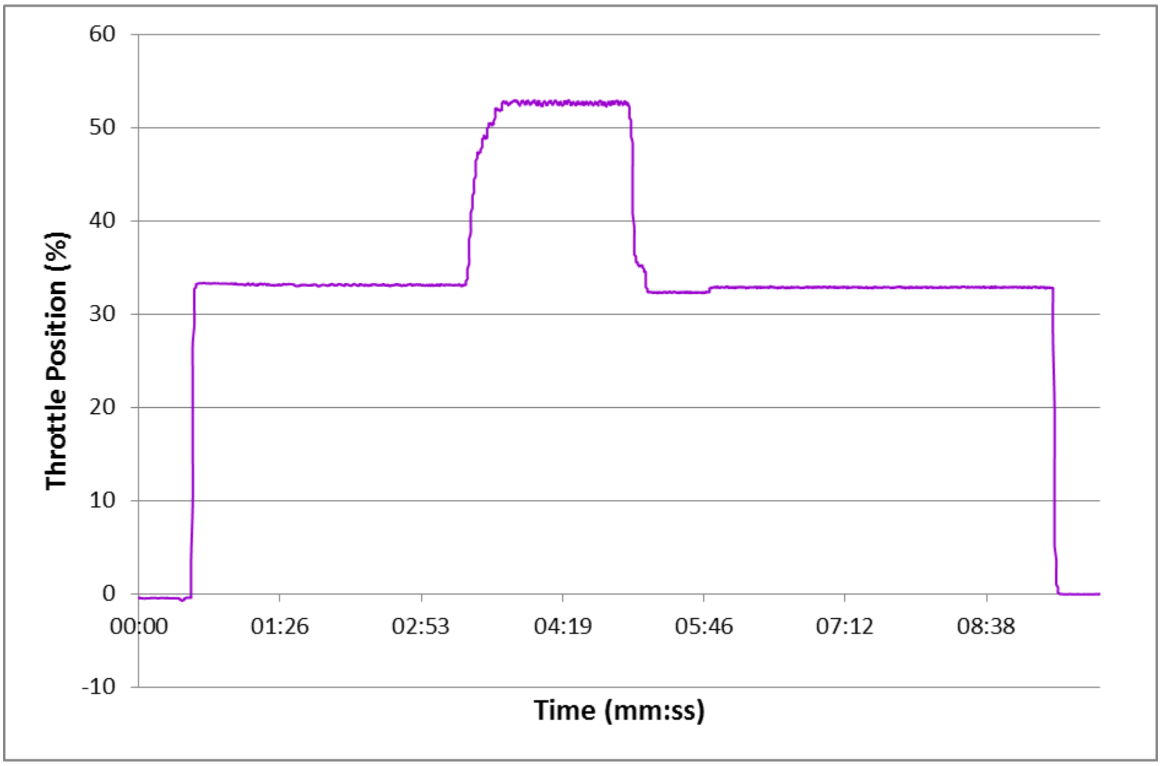


Figure 58: Throttle positioned by human operator actuating a control lever- Run 1

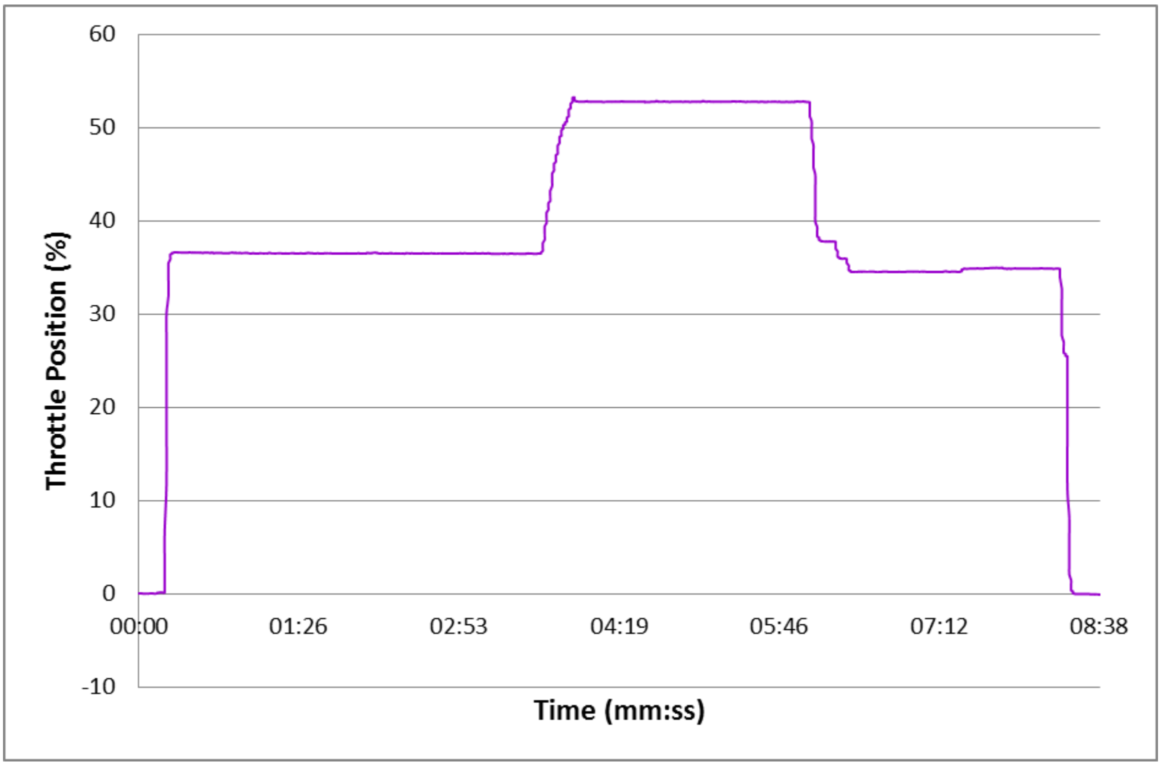


Figure 59: Throttle positioned by human operator actuating a control lever- Run 2

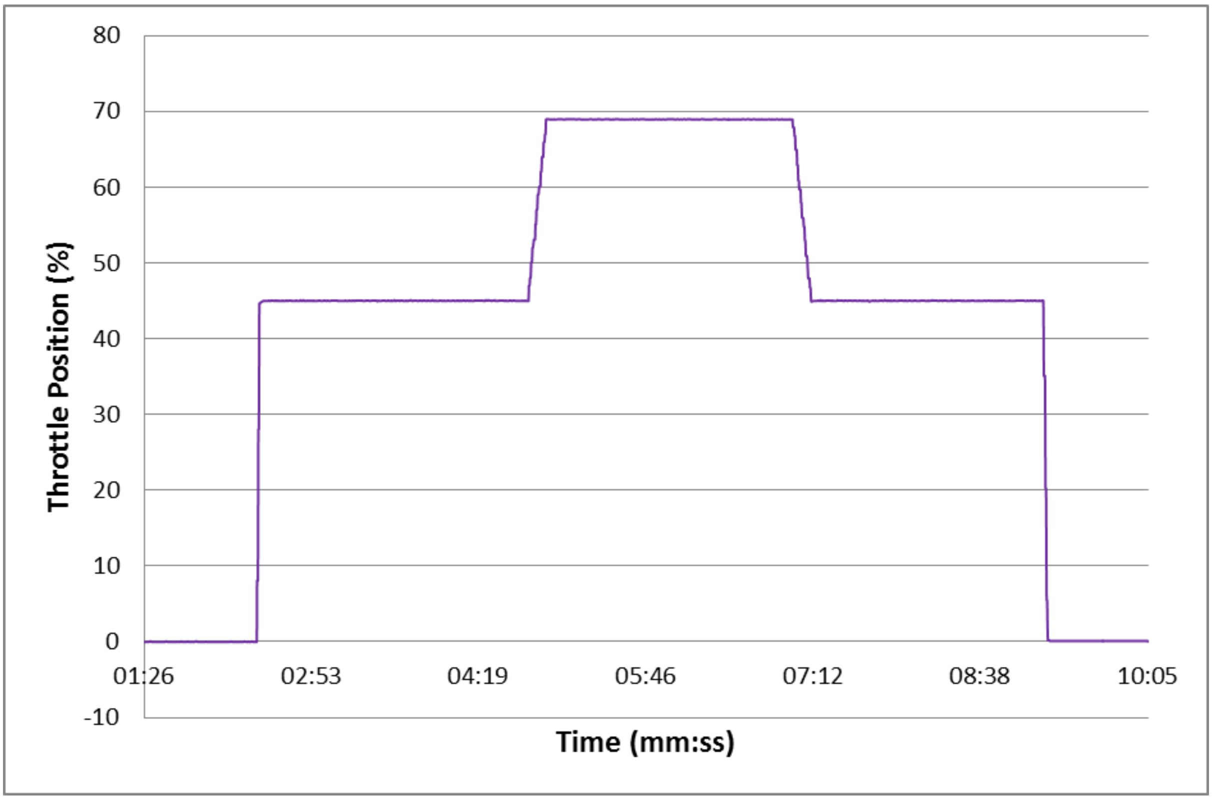


Figure 60: Throttle positioned by automated actuator- Run 1

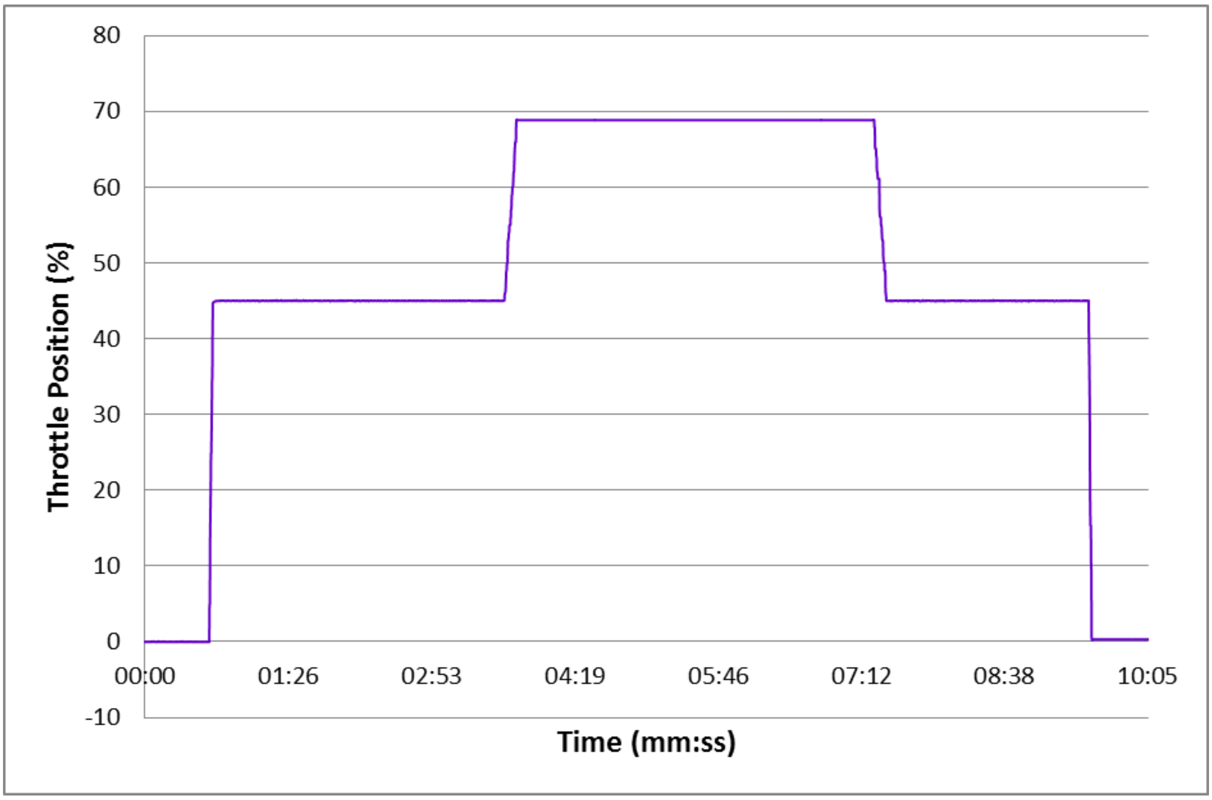


Figure 61: Throttle positioned by automated actuator- Run 2

6.2.3. ETA Automation Tests

With preliminary testing completed a pioneer automation system could be created to test viability and to determine parameters for the final version. The ETA software was programmed to run automated sequences for engine operations, refer to Section 5.4.4 for further information. Each of the phases was tested individually beginning with the testing of the automation sequences for the valves, actuators and dynamometer. The gas turbine was not run during these initial tests; instead the sensor feedback was simulated to replicate conditions in the gas turbine during runs. Tests were carried out to ensure that on receiving the specified sensor feedback, ETA correctly signaled the respective devices accordingly. Once appropriate operation of each of the devices had been verified both individually and working as a complete system, the test runs were repeated while operating the T63 and using real sensor feedback. These sequences were then refined progressively till a suitable stencil had been fabricated for facilitation of automation in LabVIEW. Foundation phases tested were as follows (traces of the results from each test appear below; note that at the end of each test run air was vented though the engine by spooling two or three times thus preventing after-fires):

- Engine startup and acceleration to a stabilised ground idle state & engine shut down from ground idle:

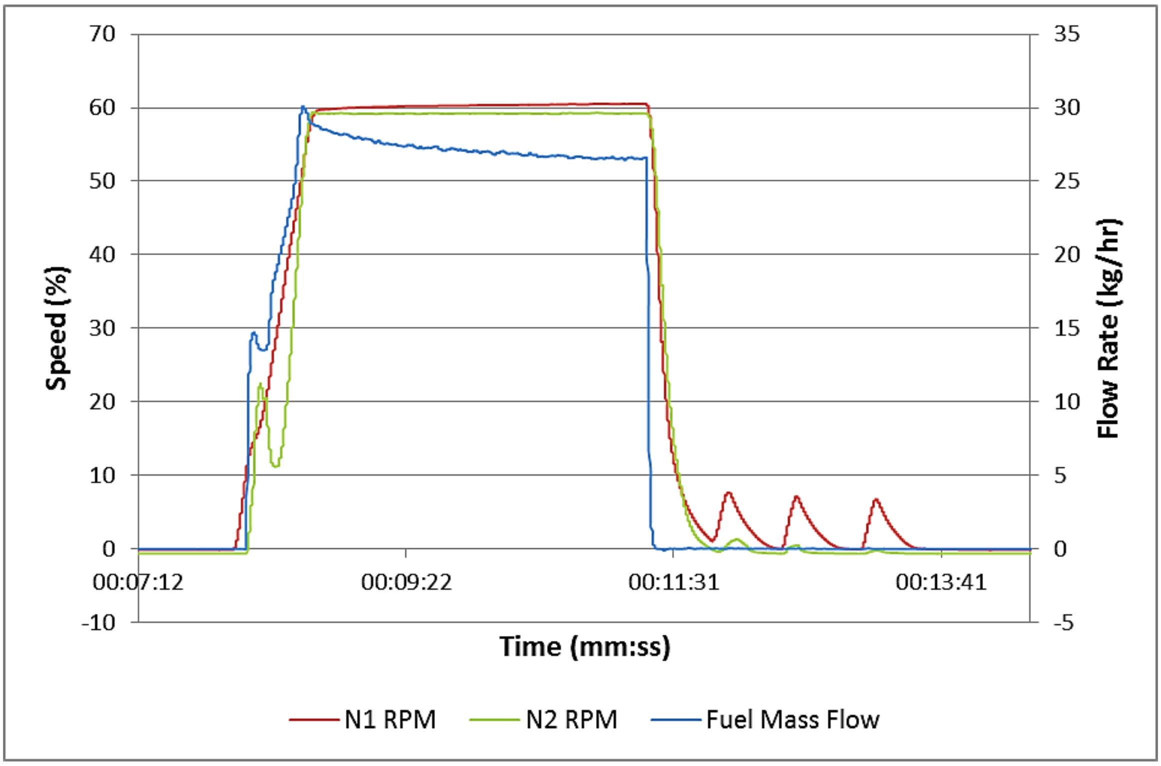


Figure 62: Fuel flow rate & turbine speeds during automated ground idle run

- Acceleration from ground idle to flight idle & deceleration from flight idle to ground idle sequence was then added to the aforementioned sequence to give a full startup and shut down sequence with suitable pauses for stabilisation. Graphical data collected is presented in Figure 63 and Figure 64. Stabilisation times at certain points within the second test run repetition was altered to determine the most appropriate timing for stabilisation of parameters such as turbine outlet temperature.

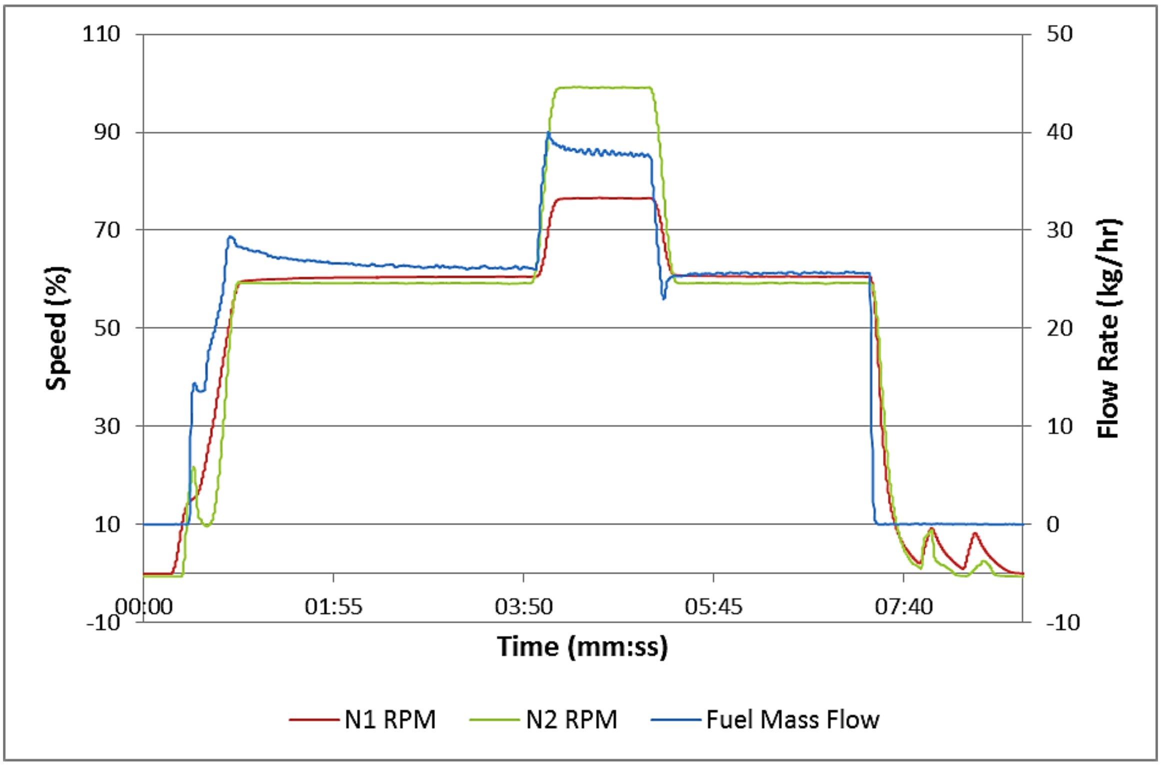


Figure 63: ETA automated start up and shut down sequence showing fuel flow rate and turbine speeds

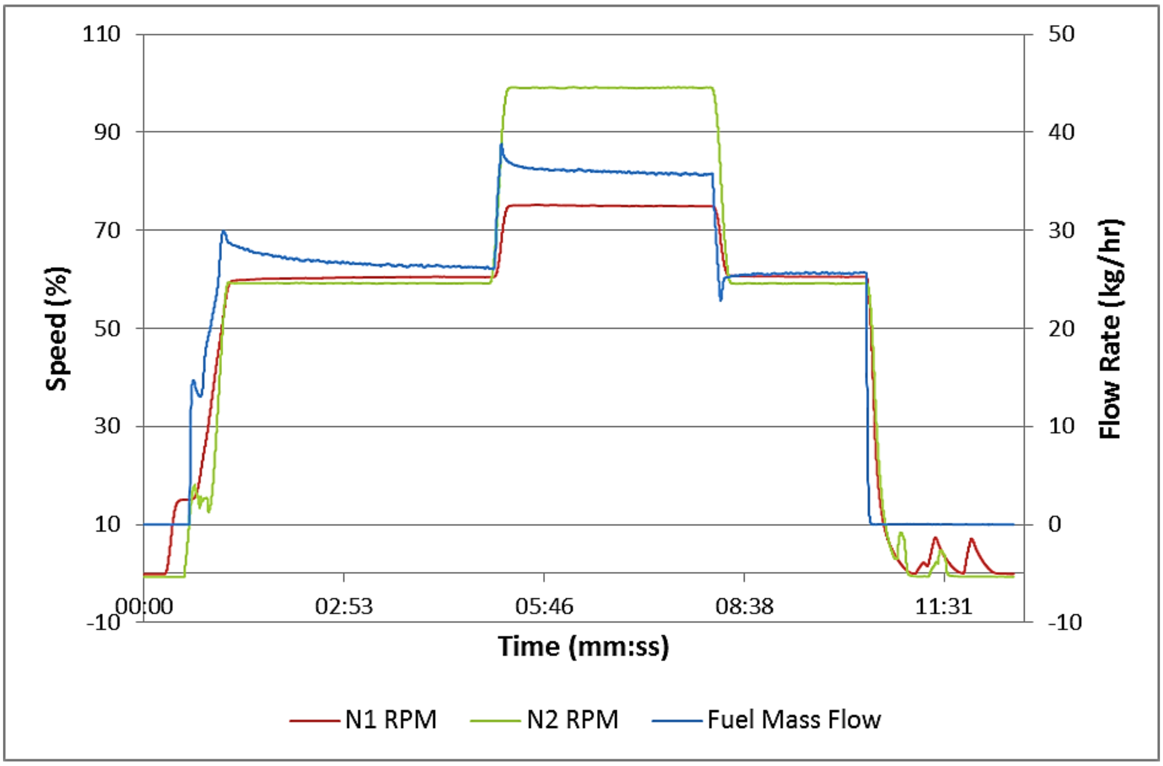


Figure 64: Subsequent ETA automated start up and shut down sequence

6.2.4. LabVIEW Automation Tests

On conclusion of the ETA automation tests it was possible to finalise the development of the automation sequences to be programmed in LabVIEW. Augmentation of this software required thorough testing of each automated process and event. This routine followed a similar format to that used in the ETA test sequence:

- The first step was to establish the correct function of the automated sequence from engine startup and acceleration to a stabilised ground idle state & engine shut down from ground idle

- The next sequence step was added giving acceleration from ground idle to flight idle & deceleration from flight idle to ground idle to give a full startup and shut down sequence.

- Stabilisation times were altered to determine the most appropriate timing for stabilisation of various parameters.

Tests were once again embarked upon in a repetitious manner starting with simple, single component tests carried out on the valves, actuators and flow meters. Gradually complexity was increased until the full system execution had been tested.

Initial testing went without impediment and the system behaved as expected- replicating speed/load behavior apparent in previous test runs. A glitch was noted at the point at which the engine speeds crested to flight idle speed. As the power turbine reached normal operating speed, the gas generator speed abruptly declined, then climbed and dropped again. This behavior continued until the engine was brought back to idle. Throughout the period that this action was displayed the throttle position was held constant however it can be seen that the fuel flow rate was erratic. This suggested that the problem was a result of the engine's response to the changing conditions. I.e.: the problem arose as a result of changes brought about by the engines governing system. The sudden changes in fuel flow caused the engine speeds to oscillate. Dynamometer torque was also affected as the x-act controller attempted to prevent the speed of the gas turbine's output shaft from escalating above the given set point, in this case 6000 rpm. Note also that the initial drop in dynamometer torque during acceleration from idle had been documented as standard behavior in previous test procedures; the engine displayed no ill effects in these cases.

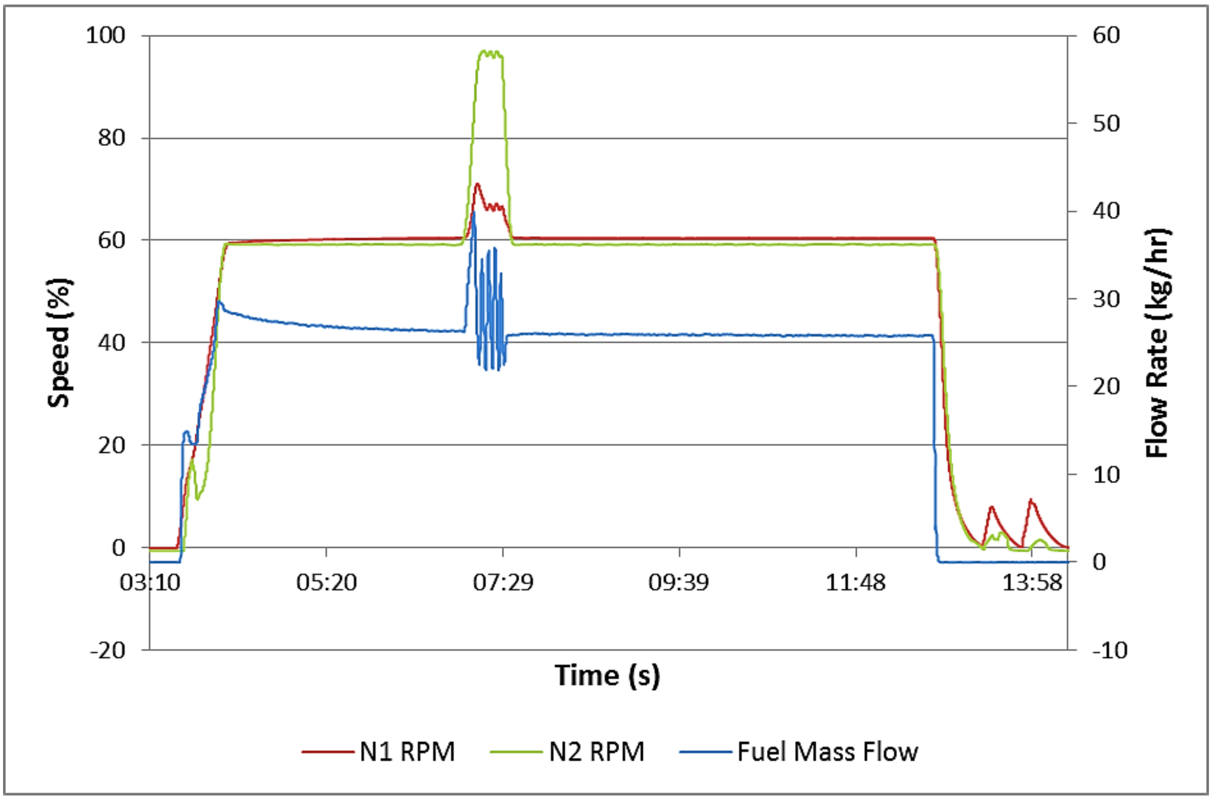


Figure 65: LabVIEW auto run with hunting

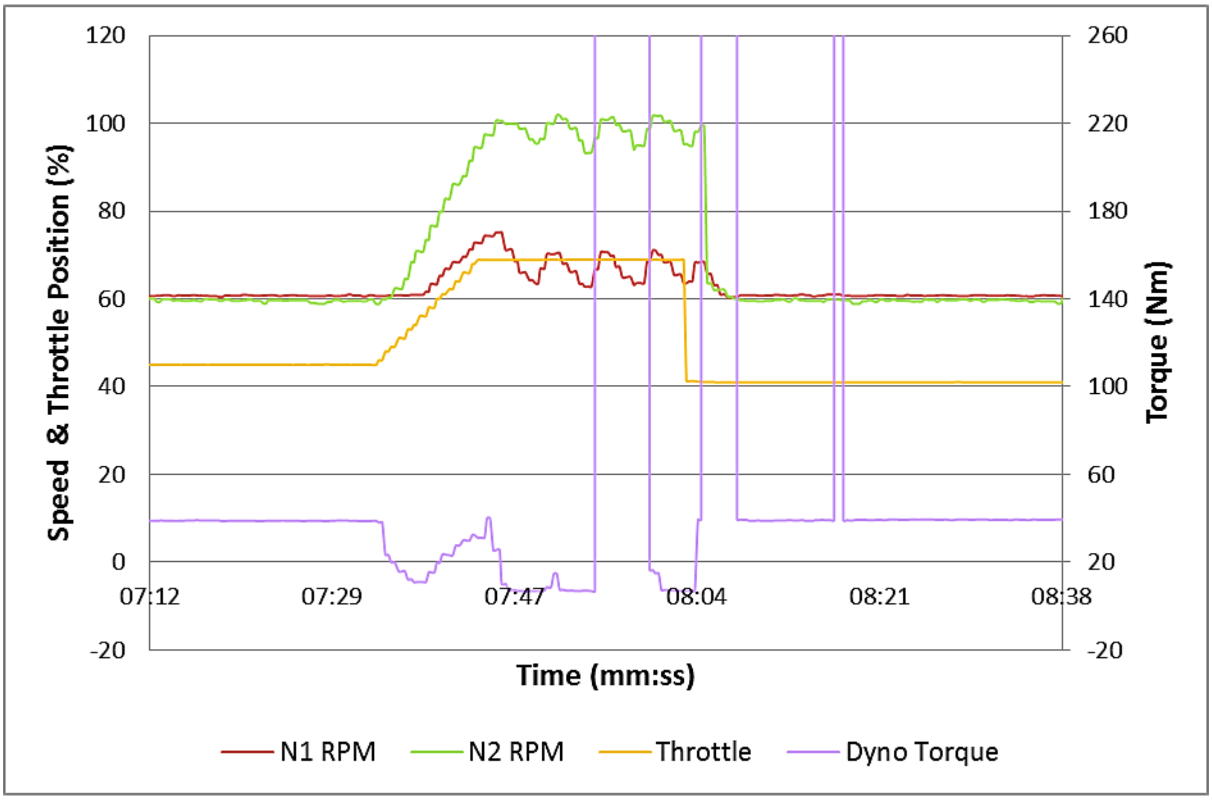


Figure 66: Torque, throttle position and turbine speed when exhibiting hunting

In an effort to correct these speed oscillations the throttle ramp rate was increased while the speed ramp rate was retained. The desired effect was that torque would be maintained at a higher value throughout the transition period. Figure 67 shows that while the dynamometer load was maintained the effect on turbine speed perpetuates. An extra flow meter and an overspeed valve had been linked between the metering valve and the nozzle of the gas turbine for the duration of the testing phase. A second venture at a solution involved the removal of the overspeed solenoid and the flexible tubing used to connect the valve to the nozzle of the gas turbine.

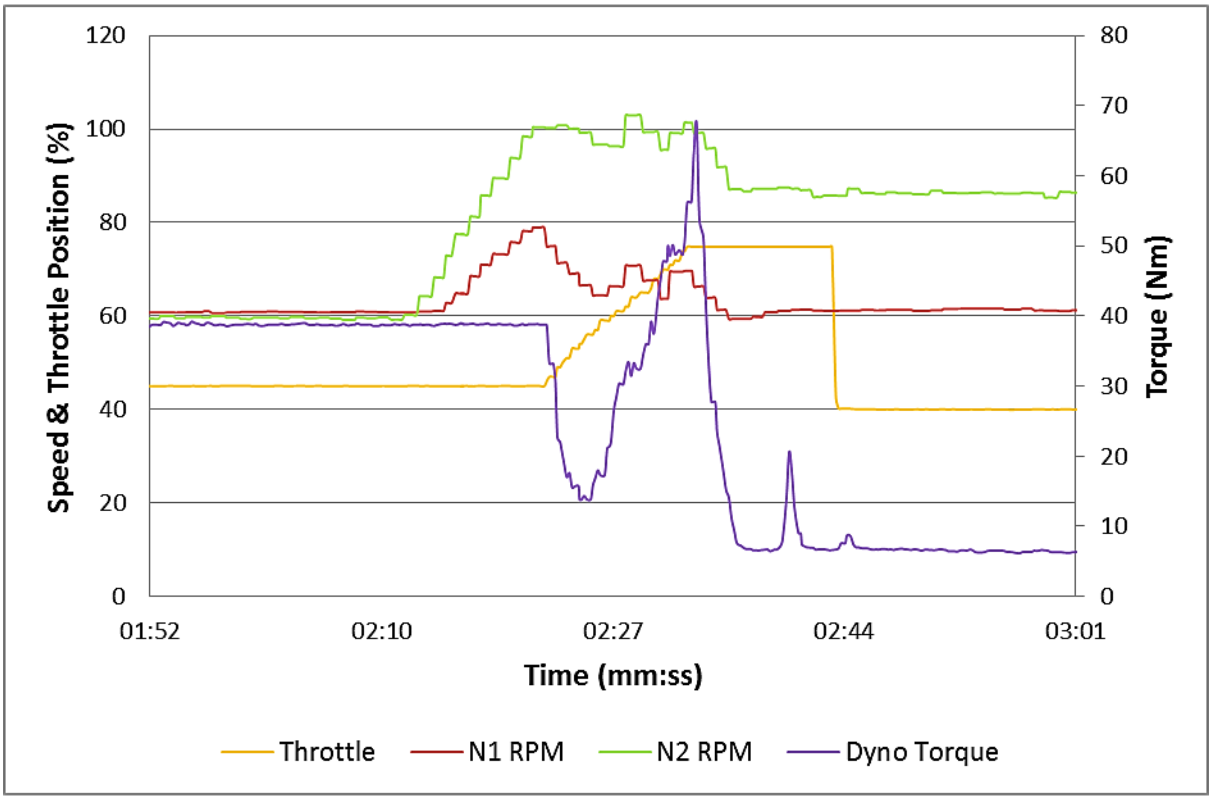


Figure 67: The effect of the disturbance on engine spool speeds

Pressure loss in this line could be calculated substituting the known variables into the Colebrook equation to determine the friction loss coefficient and the Darcy-Weisbach formula to calculate the pressure loss to give: $\Delta p\ = 0.075\ bar$. Where Δp = pressure loss (Pa, N/m^2)

Pressure loss across the overspeed valve was given as: $\Delta p\ = 0.68\ bar$.
Pressure loss in the tube and across the valve totals: $\Delta p\ = 0.755\ bar$
Or: $\Delta p\ = 4.7\%\ of\ nozzle\ pressure\ at\ flight\ idle$

The tubing connecting the metering valve to the nozzle had 1/4 inch inner diameter. The tubing connecting the valve to the original system was maintained at the same diameter. Thus a proportional loss occurred in the flow of fuel to the nozzle.

Removing this extra length of fuel line and the valve led to an increase in fuel pressure and in turn in volume fuel supply to the engine. This resolved the problem and further engine runs were undisrupted by any perturbations, as evidenced in Figure 68.

On conclusion of the test phase the additional Micromotion flow meter and tubing linking it to the metering valve and fuel nozzle were to be removed from the system. The pressure drop across this flow meter was: $\Delta p = 1.64\,bar$ equivalent to a 10.25% of nozzle pressure at flight idle. This would therefore result in a decrease in the pressure drop and would allow the inclusion of the overspeed valve once more, with no ill effect.

The final commissioning testing of the LabVIEW automation system drew the development process to a close. On conclusion of testing it was possible to pursue a final analysis of the entire development process.

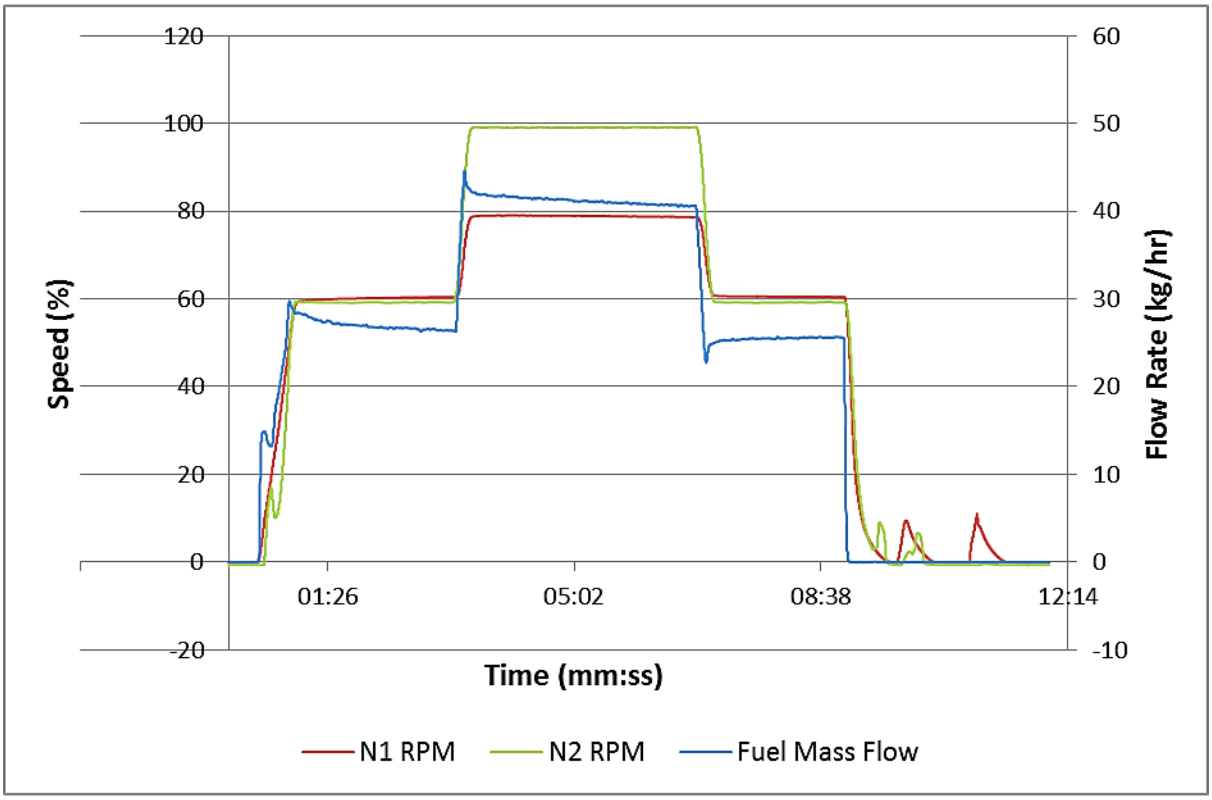


Figure 68: LabVIEW automated test run

6.2.5. System Excitation Options

Three different test sequences were run during operations at flight speed. The test results were utilised to illustrate the suitability of the control for system characterisation required for the formulation of the control law that was planned to be carried out during future projects (test results are displayed below each test description):

- Step inputs were sent to the system to increase and decrease to a given torque setting. This functionality would prove useful for determination of several system characteristics in the time domain during construction of the control laws. It should be noted that the mechanical governor of the gas turbine distorts the step inputs transmitted to it. When given a command signal the governing system of the gas turbine has certain system characteristics that alter the output of fuel flow to the engine. Thus while some data may be drawn from analysis of the response signal, further system identification procedures must be considered. The system would need to be identified and characterised before a fuel control law could be formulated.

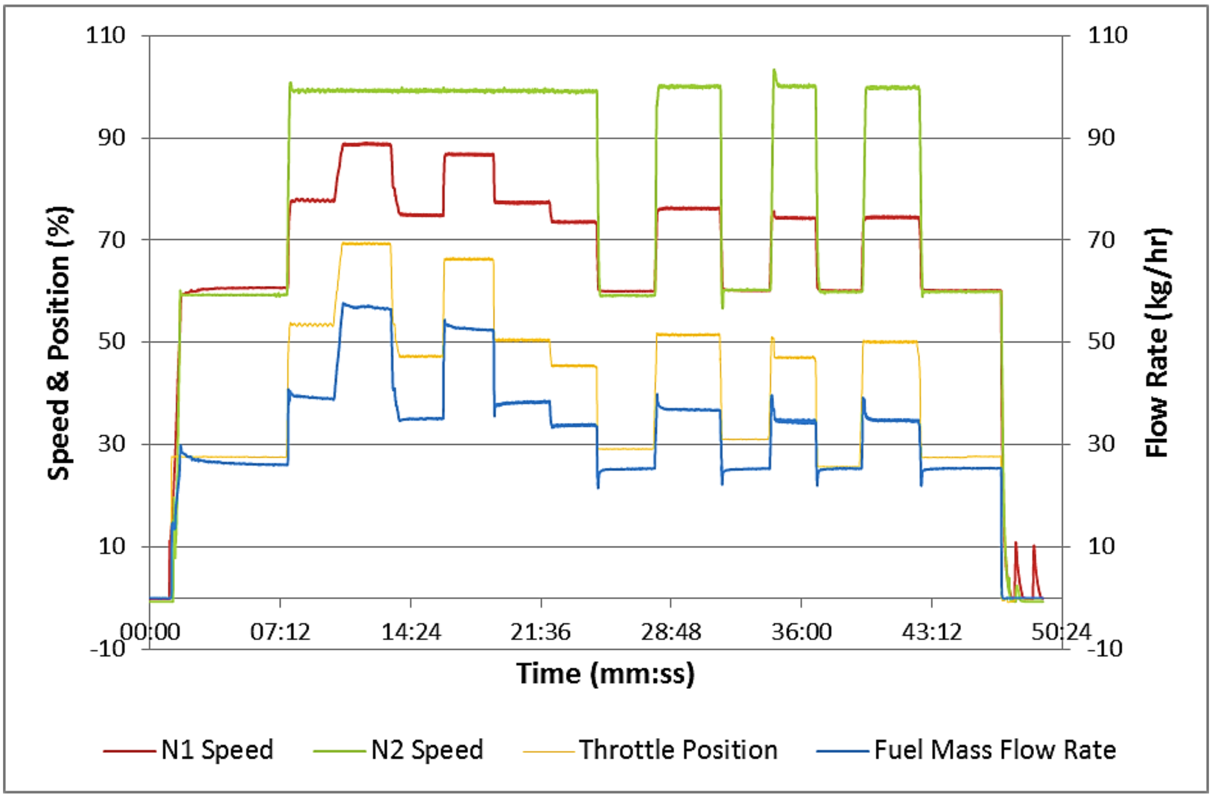


Figure 69: Fuel flow rates and turbine speeds whilst stepping torque

- Ramp accelerations were performed from flight idle to a given torque setting and back. Triangular waveforms were transmitted to the gas turbine as a means of investigating the rates at which speed, and torque could be manipulated without causing instabilities in engine operation. Once again the governor distorted the stimulus.

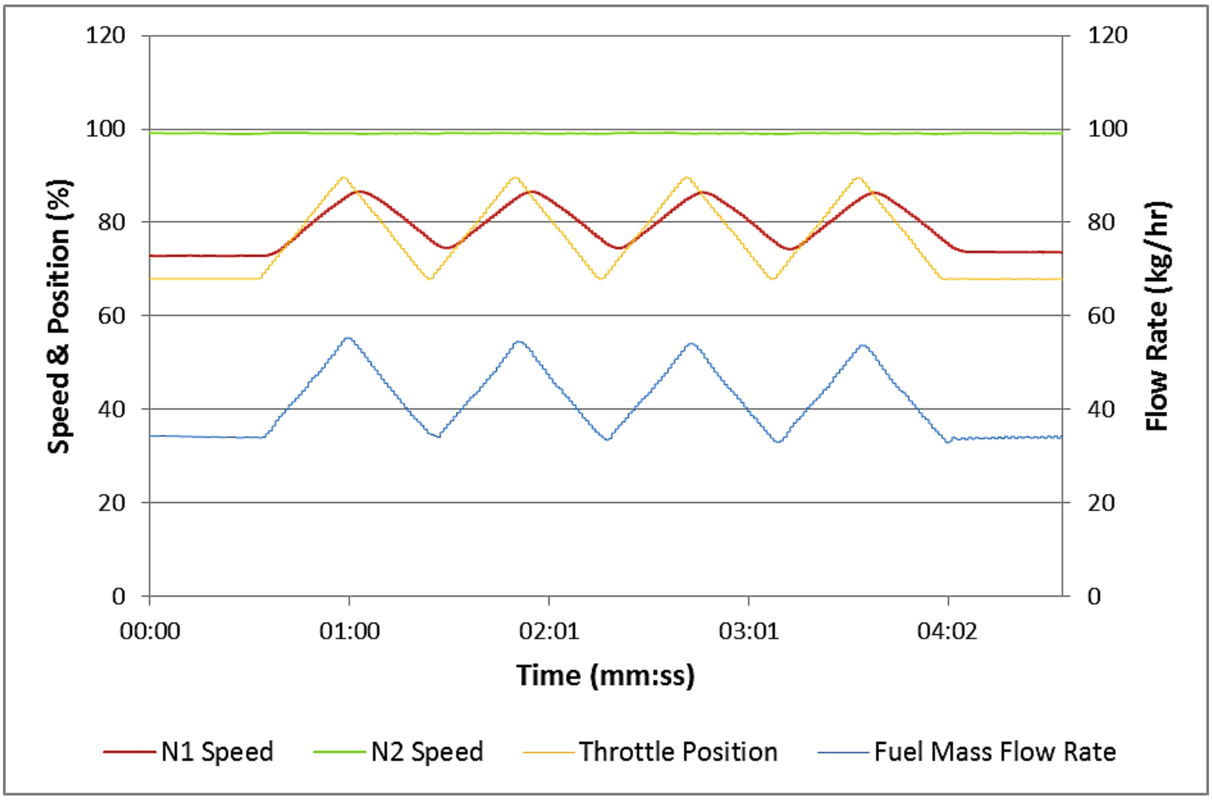


Figure 70: Turbine speeds and fuel flow rate for ramp sequence

- Sinusoidal throttle input. Results depicted in Figure 71 display the feasibility of investigating frequency excitation of the engine. The outcome of previously analysed stimulus responses implied that the frequency response of the system would be a valuable tool in identification and characterisation of the plant that was to be controlled. Tests were performed utilising sinusoidal waveforms of varying amplitude and frequency to ensure meaningful functionality of the signal generation capabilities of the electronic control unit. The output signal differed in amplitude and there was a phase shift however frequency characteristics were retained. Results also indicated that sufficient time would need to be allowed to ensure stabilisation of the system before meaningful readings could be taken since frequency response analysis methods assume a steady state harmonic system.

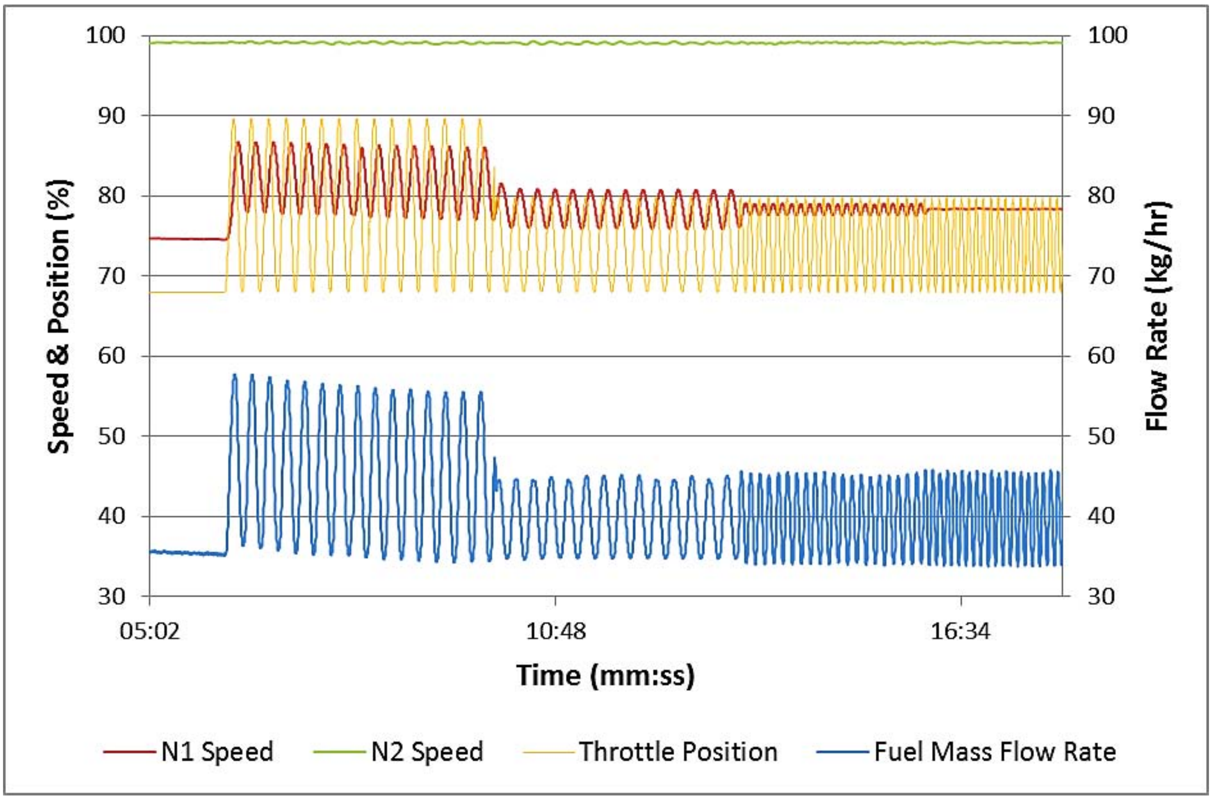


Figure 71: Fuel flow rate and proceeding turbine speeds during frequency excitation

Comprehensive system characterisation was beyond the scope of this project however some initial observations have been made. Two frequency sweeps were carried out on the system, the first at varying amplitude and frequency and the second at constant amplitude and varying frequency from 0.1 to 14 rad/s. Data from these two tests is presented in Figure 72 and Figure 73 respectively. In both examples the gas generator ceases to emit a frequency response above a frequency of 1 rad/s. This suggests that the response of the turbine was damped below this frequency, most likely due to rotational inertia. This any stimulation with a period of less than 6.3 seconds is unlikely to affect the system.

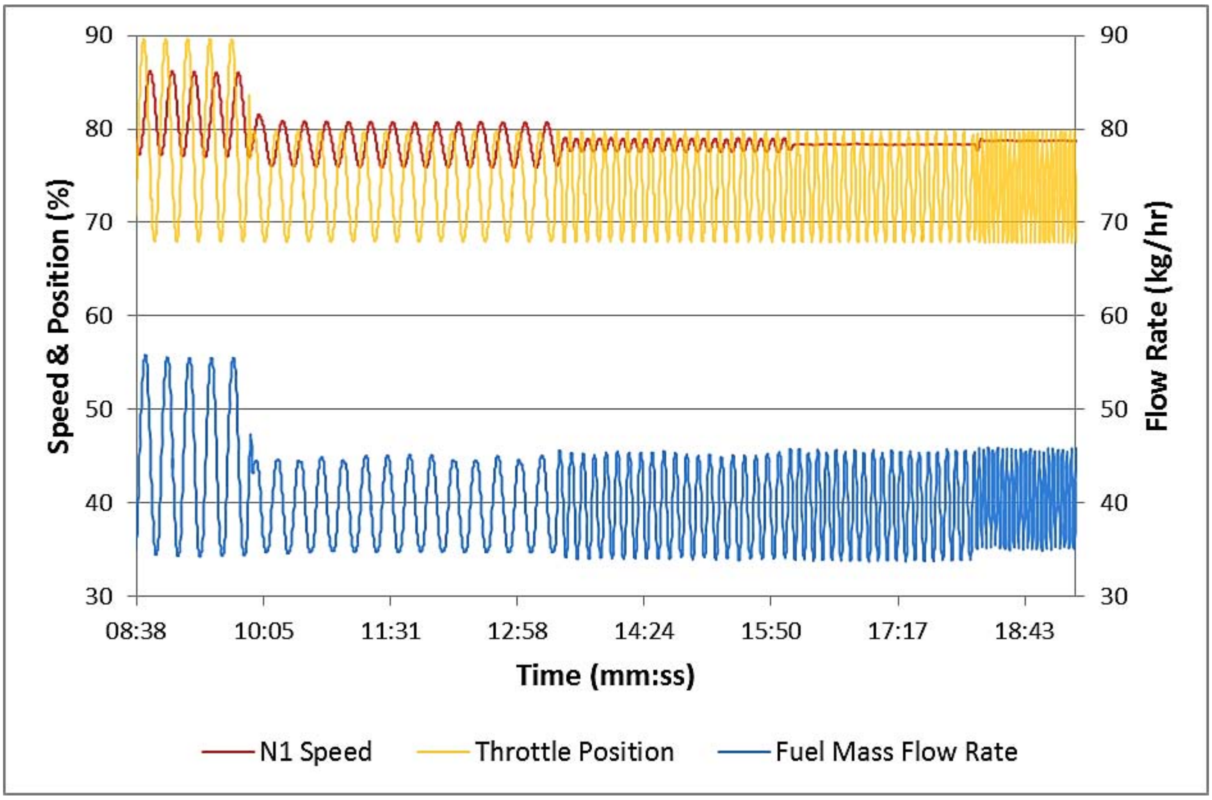


Figure 72: Data portion obtained while varying amplitude and frequency

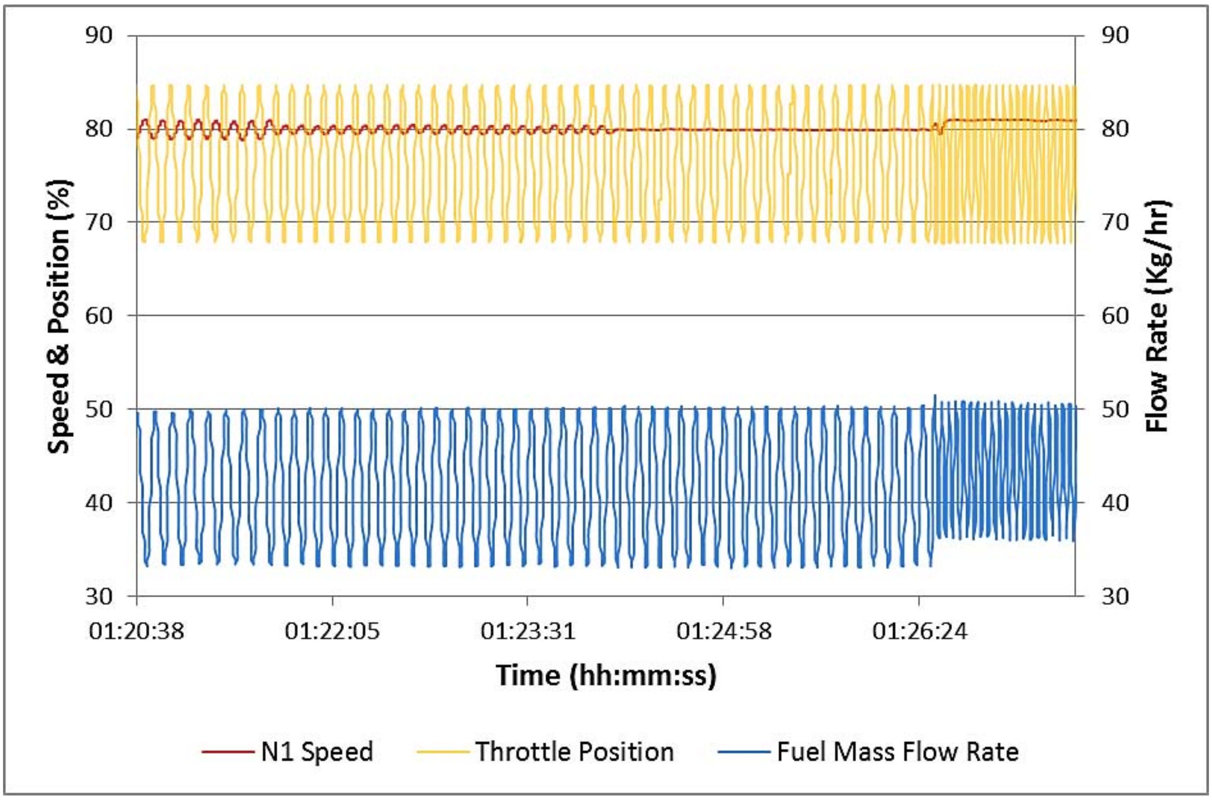


Figure 73: Data segment from run in which only frequency was varied

7. Conclusions & Recommendations

A fully functional electronic control unit was designed and created for the T63 turboshaft engine thereby fulfilling the objectives laid out for Phase 1 in the project proposal. A systematic approach was taken to the design problem and an iterative methodology applied to produce an electronic control unit which proved to be a successful amalgamation of both hardware and software. A redundant fuel control system with a hybrid design (mechanical & electronic controllers) and a software based controller was pursued when the literature review revealed this as the more cost effective solution providing greater flexibility and options for future reconfiguration. The final concept selected involved the addition of an electro-mechanical fuel controller to the existing system HMU. This concept best met both the user specified and technical requirements of the device as well as offering the highest degree of flexibility. Push button automation of the system was achieved and measures taken to ensure safe operation during runs and in the event of a power or system failure. The ECU fulfills the user specifications achieving greater precision, accuracy and repeatability than originally possible.

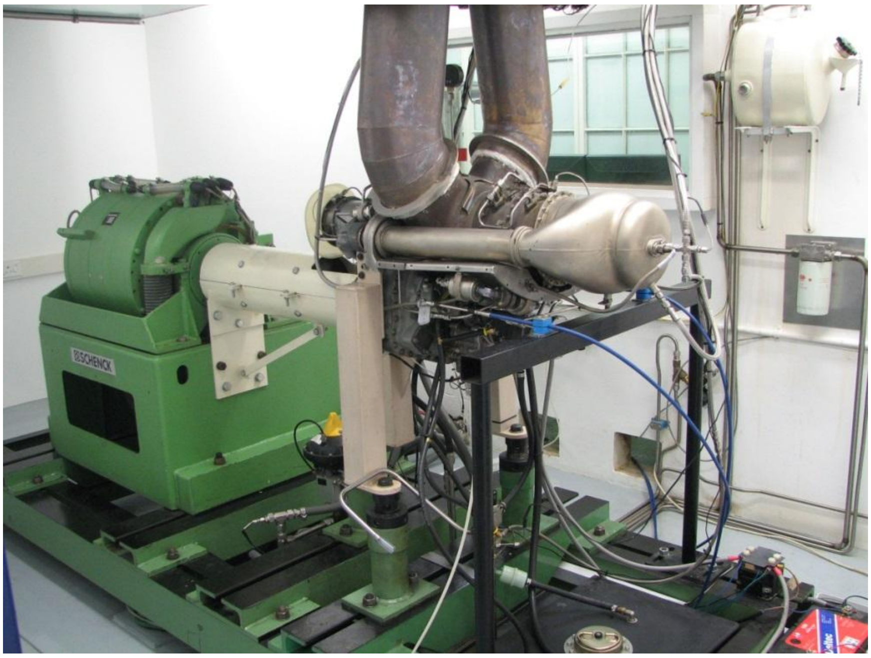


Figure 74: View of the test cell interior showing gas turbine and dynamometer

A theoretical model of the gas turbine cycle was used to complement the experimental measurements. This enabled access to additional information regarding parameters that were difficult to measure or were not measured. It was established during testing that the engine performance was not satisfactory or suitable in its initial state. Front end loading was required in the form of commissioning testing of the original system. Alterations were made to correct engine surge conditions experienced when at full speed as well as to prevent turbine overspeed. It was found that the control system for this laboratory application could not be developed in isolation of the dynamometer control system thus an application was created to facilitate communication to and from the dynamometer and throttle controller. This led to improved engine performance that can be attributed to the dynamometer automatically managing the engine's output accurately and in a stable region at all times. A modelling calculation was used to derive the theoretical combustion stability envelope from which the thermal implication of a combustion flame-out could be evaluated.

Time allocation initially laid out in the original Gantt charts created during the project planning phase was optimistic. An extended development time was required for the project due to time required for diagnostics and problem solving during commissioning of the original test cell installation and the developed system as well as procurement issues and extensive lead times on certain components. Each of these was deemed necessary and unavoidable.

Recommendations are as follows:

- Electronic control of the compressor bleed valve has been shown to give improved control of compressor surge. Inclusion of this functionality may give better control of engine performance near boundary conditions and thus more conclusive test results when investigating the effects of various fuels on threshold combustion.
- Alteration of the Bypass Valve located in the oil lines of the Power Take-off system would be a welcome modification. This valve must be continually adjusted to account for pressure changes as the oil heats up and cools down. This diminishes the possibility of oil transfer between the Main Engine Oil tank of the test cell and the PTO tank, and can become tiresome.
- The unit that handles cooling of oil returning from the engine has been noted as no longer sufficient for operations requiring a torque output higher than 180Nm. If testing is to be carried out above this limit the cooling unit should be replaced.

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Appendix A:

T63 Gas Turbine

The Sasol Advanced Fuels Laboratory T63 Gas Turbine

List of Figures

1. Introduction

The RR-Allison T63-A-700 turbo shaft gas turbine, model 250-C18B, was commissioned for use in the Mechanical Engineering department as part of a Masters project in 2008 by Nigel Bester. The intended use for the engine was to provide a test bed for fuel testing. The engine was originally selected for use at the Sasol Advanced Fuels Laboratory due to its pressure ratio and power output, which are in a comparable range to those attained with modern gas turbines, while the relative low cost of the engine maintained affordability.

The following section deals with information pertaining to this particular gas turbine, its sub-systems and those of the test cell that may need to be handled or be monitored by the ECU.

2. Fluid Supply Systems

Fluid supply to the engine is essential throughout the engine operating procedure. These fluids must be provided at strictly regulated temperatures and pressures and thus need to be carefully monitored. Each of the following sections details the three main fluid supply systems which perform these tasks.

2.1. Fuel Supply System

To maintain optimum performance of the gas turbine fuel flow must remain between 28kg/h at idle conditions and 100kg/h at take-off power. This necessitates that fuel supply pressure be maintained at approximately 0.5 bar via a back pressure regulator. Holding pressure here is confirmed by a pressure gauge that is fitted upstream. This ensures a constant delivery of fuel as well as preventing cavitation in the high pressure fuel pump.

Ball valves and isolation valves were incorporated into the supply system for use during purging and for emergencies respectively. A pneumatically actuated emergency shut off valve utilised ~7bar compressed air, the supply of which is controlled by a solenoid valve that was normally closed unless signalled from the **P**rogrammable **L**ogic **C**ontroller (PLC). A single supply line ran to the engine with no return line thus fuel flow could be measured on this line using a fuel flow meter. The temperature and pressure of the fuel supplied was also measured and read into the PLC allowing conversion between volumetric and mass flow rate. Maximum pressure throughout the system was 1 bar gauge or 2 bars absolute. [5]

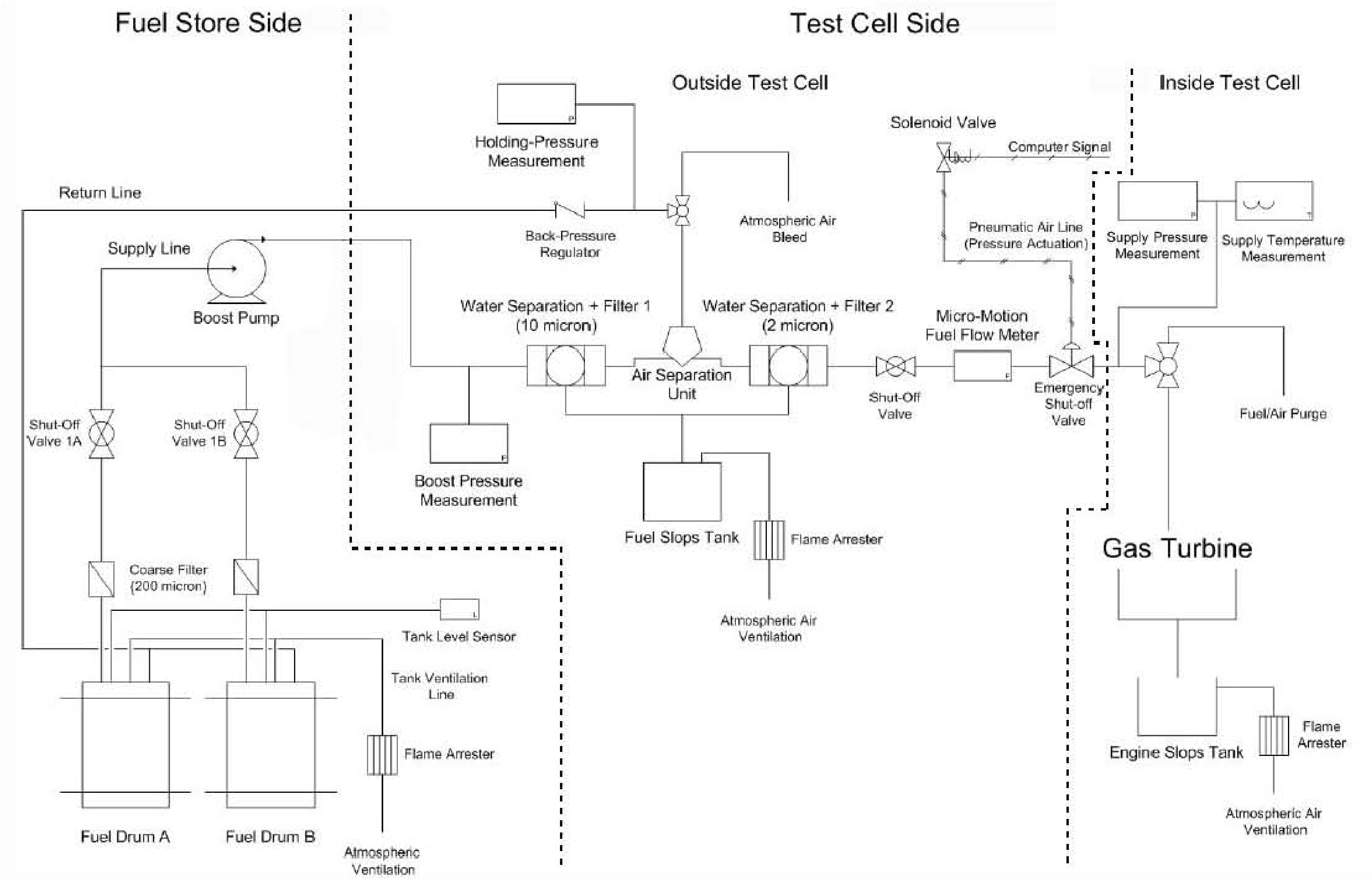
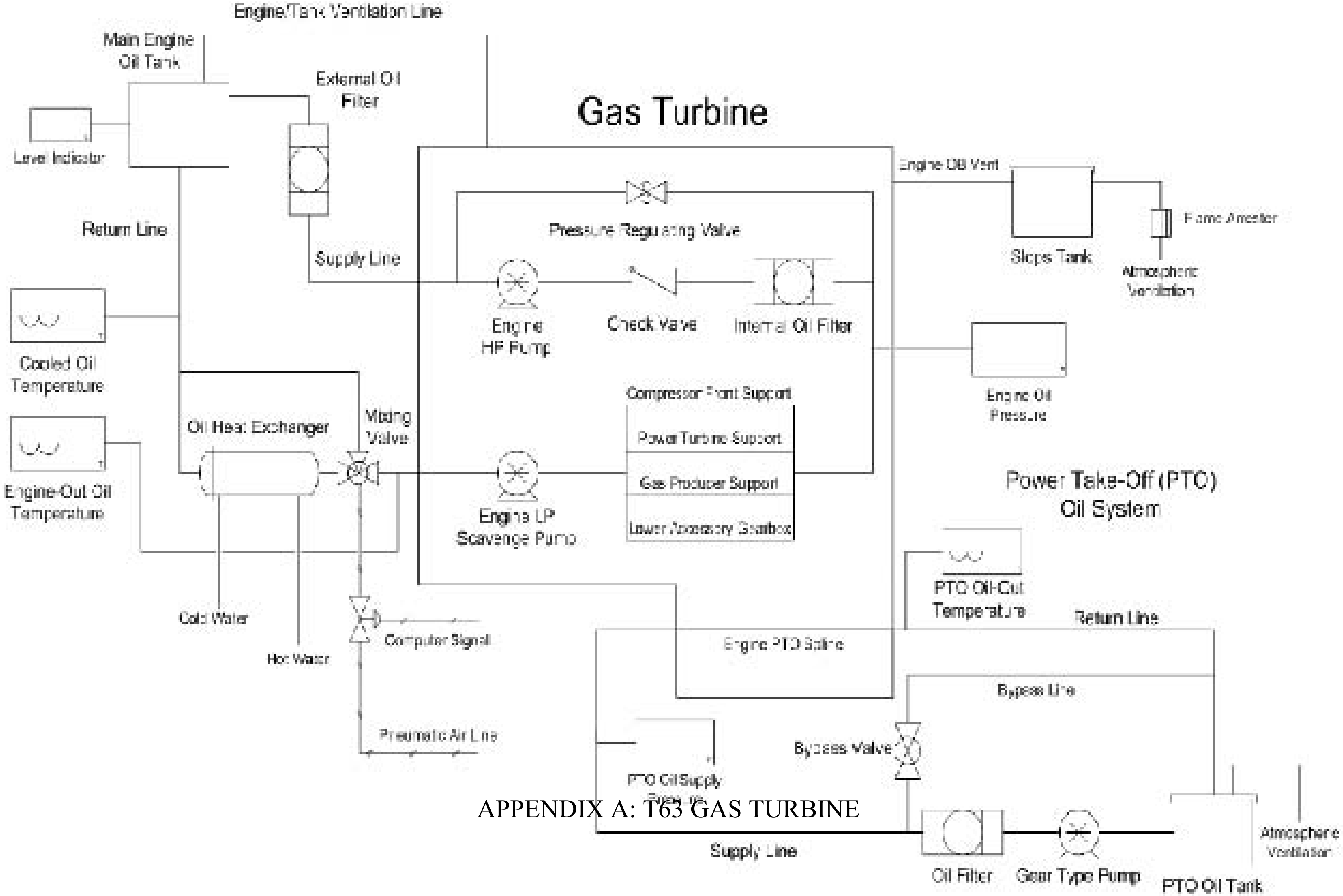


Figure_ A-1: Fuel supply system of the T63 [5]



APPENDIX A: T63 GAS TURBINE

Figure_ A-2: Oil supply system of T63
[5]

2.2. Oil Supply System

Oil was supplied to the system via a gravity feed, the oil is then pumped around the engine by means of the high pressure and scavenge gear pumps normally found on a helicopter type set up. Oil temperatures were monitored on its leaving the engine and the signal read via a PLC into the controlling computer. A mechanical pressure gauge and pressure transducer continually measure oil pressure.

A **P**ower **T**ake-**O**ff (PTO) oil system was also constructed; this provides lubrication to the gas turbine output shaft spline as well as the free-wheeling unit. This system contains its own pressure transducer, linked to the PLC, and thermocouple monitoring oil exit temperature.

There are no shut off valves included in the oil system as can be seen in the layout shown in Figure_ A-2. [5]

2.3. Water Supply System

Water acts as the coolant for both the eddy current dynamometer as well as for the engine via the oil system. Measured variables monitored to confirm proper performance from the system were the water supply pressure and dyno-out temperature. [5]

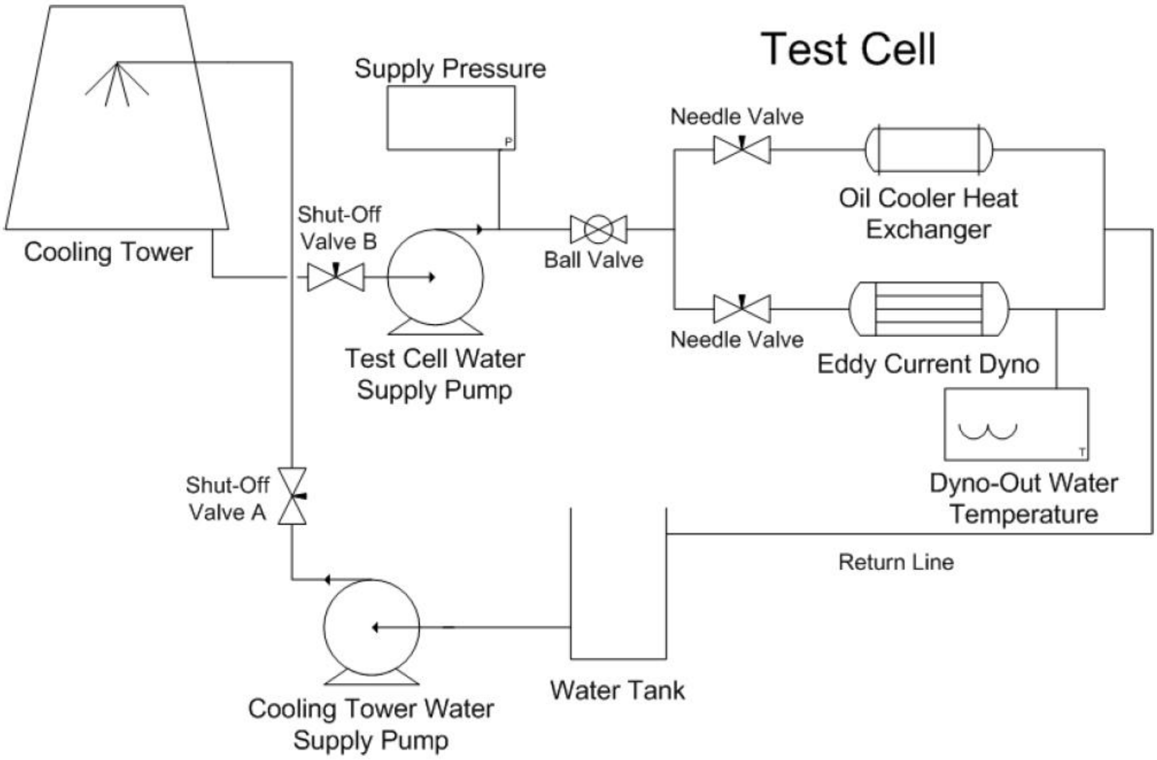


Figure_ A-3: Water supply system of T63 [5]

3. T-63 Fuel System

The fuel system of the T63 is made up from a number of components which function mutually in order to maintain the correct fuel flow to the engine over the course of its operation. These components can be grouped into three main devices namely the fuel pump, gas producer fuel control and the power turbine governor. An illustration showing the fuel system components can be seen in Figure_ A-4 overleaf. [40]

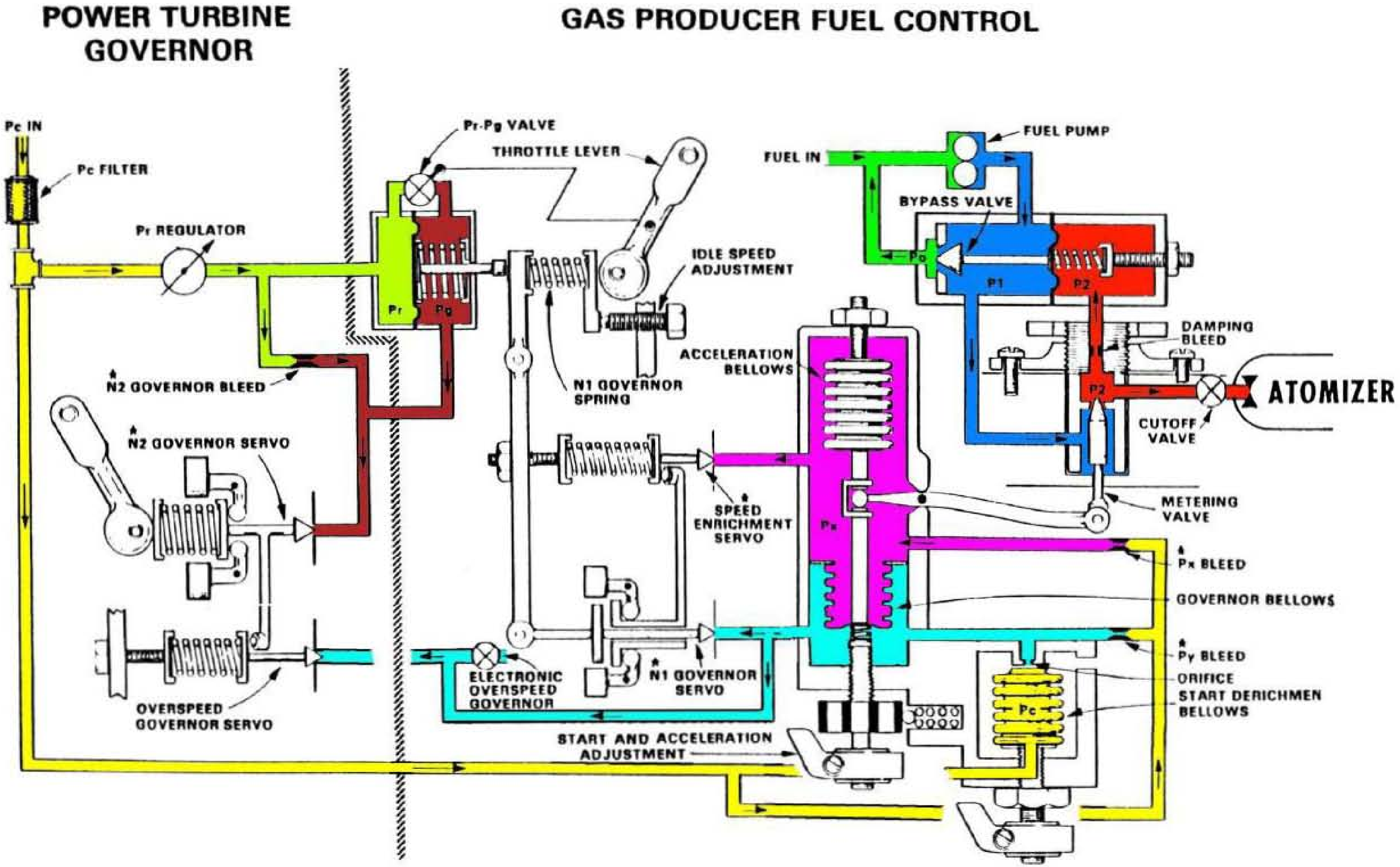


Figure_ A-4: Bendix fuel system

[40]

Key for Figure_ A-4:

Air pressure:

P_C	Compressor discharge pressure
P_R	Regulated pressure line
P_G	Pressure to governor line
P_X	Pressure over the sealed acceleration bellows
P_Y	Pressure over differential bellows

Fuel pressure:

P_{F0}	Fuel supply pressure
P_{F1}	Pressure after fuel pump
P_{F2}	Pressure after metering valve

3.1. Gas Producer Fuel Control

This section will look at each of the components that make up the gas producer fuel control system individually starting with the fuel pressure regulator.

The fuel pump draws fuel from the supply line and conveys it past the metering valve to the atomiser. Opening and closing the metering valve causes a diaphragm in the differential pressure regulator to expand or compress in response to the change in pressure, $P_{F1} - P_{F2}$, maintaining it at a constant value (where P_{F1} is blue and P_{F2} red as shown in Figure_ A-5). If the fuel supply pressure were to decrease this would cause the fuel flow rate across the metering valve to be reduced. This in turn would lead to a decreasing pressure drop from P_{F1} to P_{F2} causing a smaller change in pressure across the diaphragm in the pressure regulator thus the bypass valve will shut and close the return line. [40]

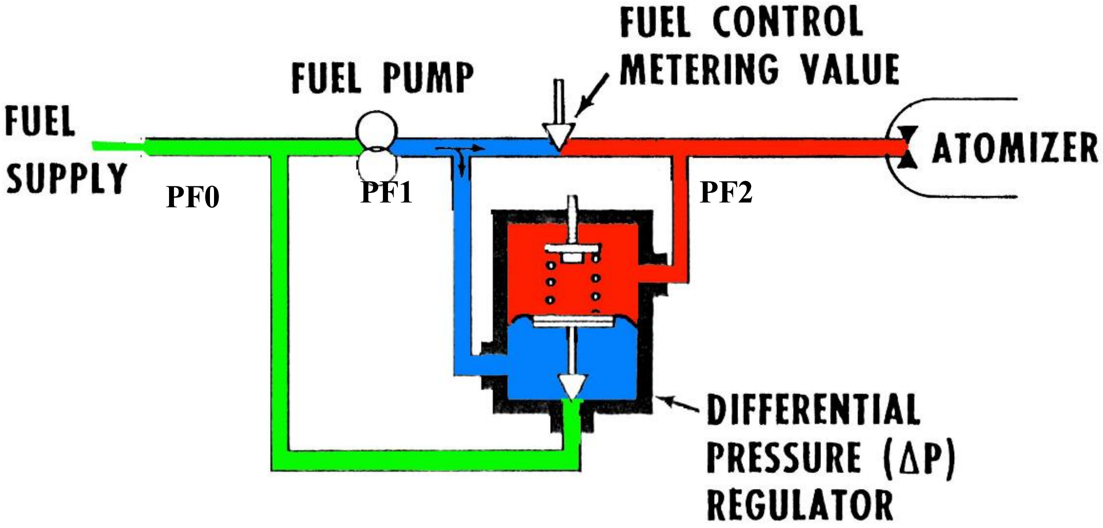


Figure_ A-5: Fuel pump and bypass system [40]

The governor and acceleration bellows work together to operate the lever that moves the metering valve. The metering valve regulates the flow of fuel and thus flow rate is a function of the metering valve position. Thus in normal acceleration the governor valve remains seated and fuel flow will rise with air pressure. However if the governor valve is opened the pressure over the differential bellows (P_Y) will drop thus moving the lever arm and therefore the metering valve to decrease fuel flow thereby limiting the gas producer speed (N_G). [40]

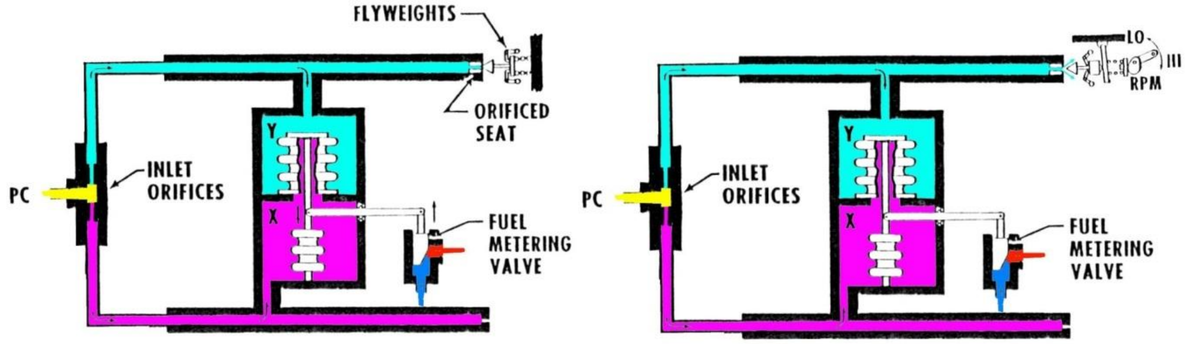


Figure_ A-6: Governor and acceleration bellows working to move metering valve [40]

Also contained within the system is a start derichment valve, when this is opened the compressor discharge pressure (P_C) is vented to the atmosphere. This causes the metering valve to allow only minimum flow or lean fuel scheduling. Functioning over the course of operation:

- Before light off
    - P_C is equal to ambient pressure therefore the metering valve is set at a home position.
- During light off & initial acceleration
    - Start derichment valve open until a certain value for P_C is reached at which point the derichment valve is closed via the derichment bellows. At this point control of the metering valve returns to normal.
- During acceleration
    - $P_X = P_Y = P_C$ until speed enrichment orifice is opened by flyweights (where P_X is the pressure over the sealed acceleration bellows)
    - Opened orifice vents P_X to atmospheric pressure
    - Change in pressure across governor bellows causes metering valve to open to allow maximum flow.

There is another system set up to reset the fuel control schedule to adjust the gas producer fuel control however control of this unit originates in the power turbine governor.

3.2. Power Turbine Governor

The power turbine governor has three main functions, the first of which is to monitor the power turbine speed. A combination of the power turbine governor lever and the power turbine speed scheduling cam set the governor spring load opposing the speed weight output. The speed weights cause the linkage to open the power turbine governor orifice which in turn bleeds the pressure to the governor line (P_G). If overspeed conditions are neared the aforementioned speed weights cause the P_Y bleed to open at the power turbine governor thus providing a rapid response to prevent overspeed. This device can be seen in Figure_ A-7. [40]

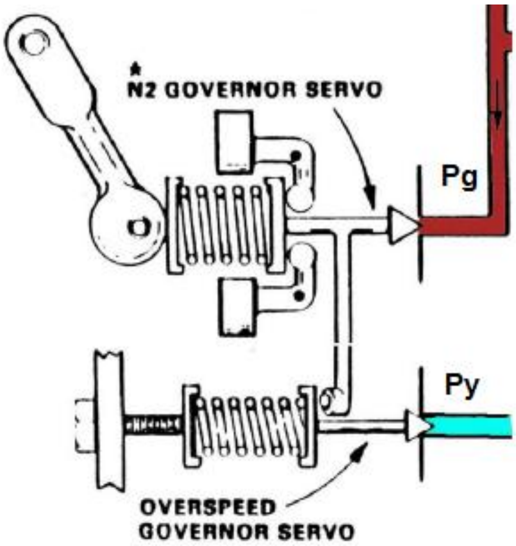


Figure_ A-7: Part of the power turbine governor [40]

The diaphragm across which P_G and regulated pressure line (P_R) act affect the gas producer power output link and is preloaded to set the active range. When $P_R - P_G$ creates a force across this diaphragm this influences the weight force in the gas producer fuel governor thus bleeding the P_Y pressure and reducing gas producer speed. The N_P governor therefore provides input to the N_G fuel control unit via P_G (pressure governor) line.

3.3. Modifications due to Test Cell Conditions

For certain reasons some modifications had to be made to the fuel system installed on the engine at the SAFL site as a result of test cell conditions. The recommended rotational inertia for a test cell drive train is 1.35- 4.05 $kg.m^2$ to mimic conditions that would be experienced if the engine were installed in a helicopter. The eddy-current dynamometer installed on site had a rotational inertia = 0.42 $kg.m^2$, which was much lower than that recommended.

Incorporation of a fly wheel to raise inertia to these limits was not desired therefore the fuel control system was modified to account for this. A controlled bleed on the P_R pressure line was incorporated thereby oscillation speeds could be minimised by reducing the magnitude of $P_R - P_G$ feedback with respect to speed. [5]

4. Electrical System

The electrical system built into the test cell as a part of the 2008 project was designed to deliver power during the start-up procedure as well as to power the fuel boost pump and other subsidiaries.

Two DC power supplies were provided that supplied +24V each, the first of these supplies was built into the test cell itself and provides up to 500A (300-400A of which were to power the starter motor).Current to the spark circuit (the spark circuit draws about 4A) and starter motor was switched on via a relay which would only activate if both the master and starter switches were activated. The starter switch was a dead man's switch that was only activated when depressed. It was also to this supply that the fuel boost pump was connected drawing ~81watts at 3.5A. A **L**ight **E**mitting **D**iode (LED) display in the control room was connected to another circuit built, with a resistor to limit current to 7mA; this circuit incorporates the two magnetic chip detectors built into the T63.

The second supply was the low current PLC power supply. The emergency shut off valve was powered from this source. [5]

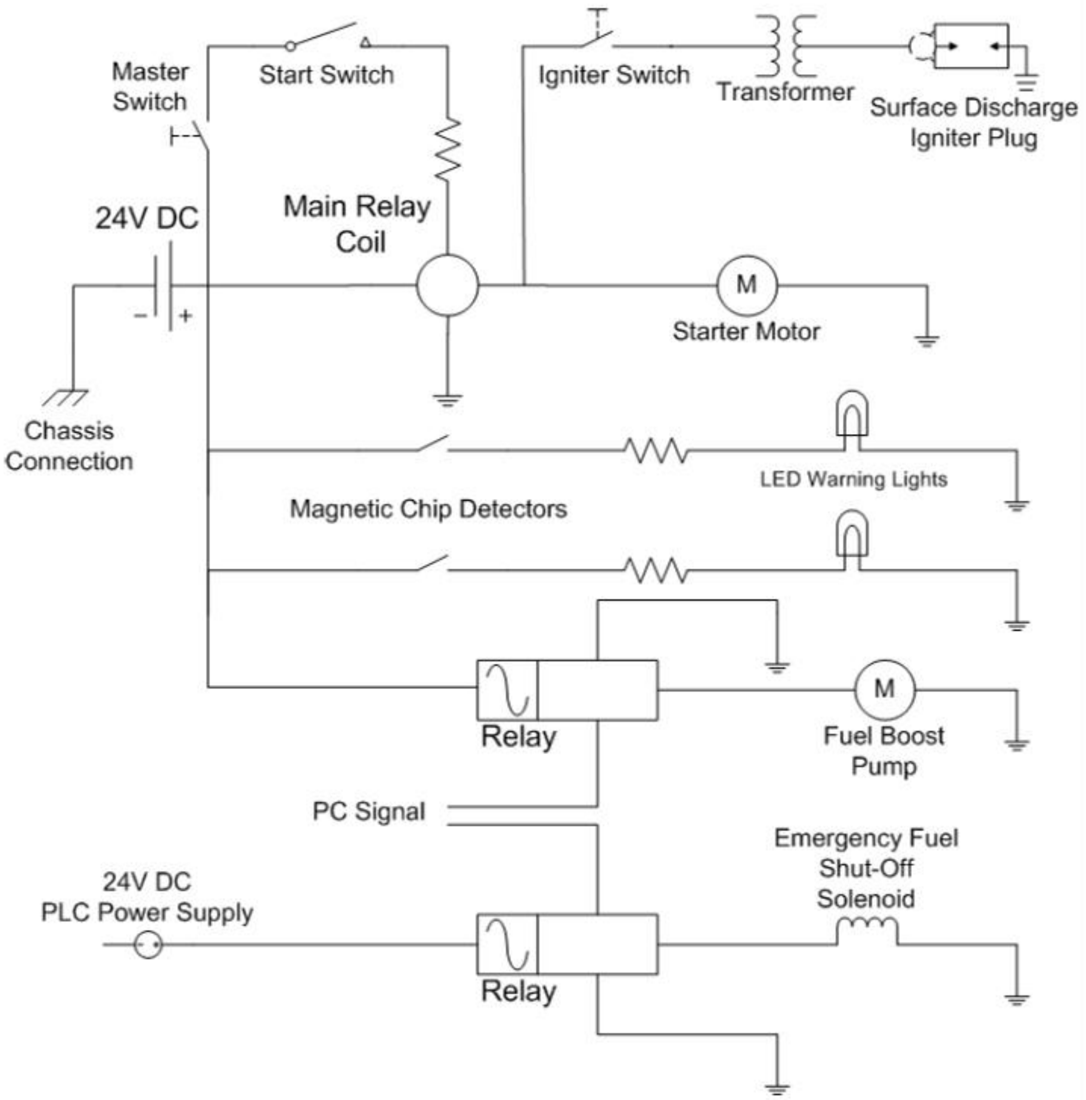


Figure_ A-8: Schematic of T63 electrical system [5]

5. Recommendations Proposed in the 2008 Project

A small number of recommendations were put forward once the first fuel testing was carried out on the T63 engine that might improve upon the performance of the system. One suggestion presented was that engine speed oscillations should be decreased by means of better dynamometer control or via the incorporation of a flywheel.

It was stated that a more accurate TOT gauge, with a deviation of ±0.1°C would be considerably better than the ±5°C precision afforded by the current gauge.

Furthermore it was mentioned that the dynamometer load could be lost in unforeseeable circumstances. This would result in rapid overspeed though this would be limited by the engine rapid overspeed response. One possible solution presented was to control the engine via an electronic throttle controller. This would allow the operator to vary the N_P throttle lever according to load, a similar system to that utilised in helicopters, allowing for transient cycle testing & additional system protection [5]

Comments: While installation of an improved TOT sensor system is recommended, time constraints on this project prevent further investigation into this issue.

Appendix B:

Detail on Digital Systems

Detail on Digital Systems

List of Figures

1. Dynamometer Communications

1.1. Communications Interface

The communications paths between the dynamometer and host computer are laid out in Figure 43. Communication with the X-act controller was facilitated by the use of CAN cards installed in both the host and target devices. CAN was a serial bus standard designed to allow multi-master communications between devices. In the case of the digital controller developed as a part of this project a National Instruments PCI-CAN/2 Series 2 interface was installed in the host computer. This card boasts two high speed communications ports and supports a maximum baud rate of 1Mbit/s, ample for communications to the 500 kbit/s CAN interface of the Schenck's X-act controller.

Communication between the host and target was achieved by transmission of messages in the form of frames. There are two frame formats in which it was possible to send messages, these being standard and extended format. Standard frame format utilising an 11 bit identifier was employed to send and receive data to and from the X-act controller. The format for a single frame was laid out in the image below.

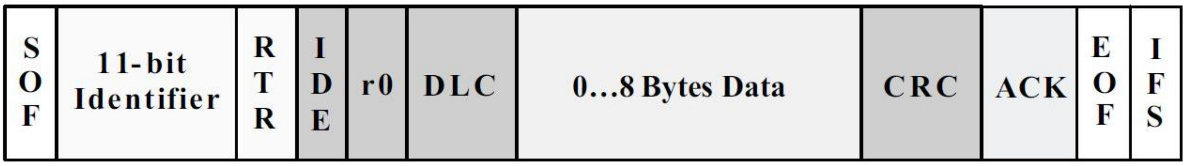


Figure_ B-1: Standard CAN frame format [57]

Key for above image:

SOF	Start of frame: indicates the start of a message.
Identifier	Priority of message established by identifier: lower binary value = higher priority.
RTR	Remote transmission request: requests data from the node specified in the identifier.
IDE	Identifier extension bit: if dominant = standard CAN identifier used
r0	Reserved bit.
DLC	Data length code: 4 bit code specifying number of bytes to be transmitted.
Data	Up to 64 bits of data may be transmitted.
CRC	Cyclic redundancy check: checksum for number of data bits transmitted for error detection purposes.
ACK	Acknowledge: a dominant bit if error free message received.
EOF	End of frame: indicates end of message.
IFS	Inter-frame space

There were four CAN identifiers that were to be used with all communications to and from the X-act controller. These were as follows:

0x0b	Offline connection: command from host to X-act
0x0a	Offline connection: data response from X-act to host
0x03	Online connection: actual value data from X-act to host
0x04	Online connection: set point data from host to X-act

1.2. Method of Communication

The dynamometer's X-act controller proffered two options for communication of data, known as online and offline communications. Each of the options bore certain characteristics that made them best for use in specific areas. Online communications required initial set up of the channels desired for use as either read only or write only. The data transfer rate was also to be adjusted to the desired rate, up to a max of 100 Hz. Synchronous transmissions of the configured type then took place periodically. Offline communications involved a command or request being sent from the host to the X-act, which then responded accordingly. Big endian IEEE floating point format was the form in which online transmissions were sent. Offline transmissions were sent in ASCII strings that assumed the form of the Standard Commands for Programmable Instruments (SCPI) syntax. Data was transmitted in SI units in the default state. SCPI commands were sent in a series of commands, up to a maximum of 1024 characters, separated by semicolons and ended in an ASCII newline symbol.

The structure of the response messages from the X-act in the case of offline communication was in the form of numeric values or text strings represented in ASCII and separated by commas or semicolons. If a number of commands were sent in series the response sequence matched that of the commands. For example if the command requested the actual values for speed and torque and lastly for current status of online communications the response would list first the value for speed in RPM then torque in Nm followed by either a 1 or 0 to indicate the communication status. Numeric numbers were sent in decimal point or scientific notation while a text string was enclosed within inverted commas.

The first byte of each data message to or from the X-act controller functioned as a descriptor. The descriptors were used as follows:

0	Reset
1	Start
2	End
3	Acknowledge
4	Not Acknowledge
5	Data Transfer (max 7 bytes)

1.3. Code Structure

The dynamometer driver was structured as three distinct state machines. Each of the three state machines was designed to handle one of the three communications protocols broken into a number of sectors or states. Data read into the system was first put through an identifier which then relayed the information on to the correct data handling state machine according to the ID code of each frame.

State machine one was programmed to deal with the online read sequence, which was set up such that the dynamometer would transmit the torque, speed, throttle, mode, ignition status and actual torque, speed and throttle set point values every 100 milliseconds across channels 01 to 08. The data was sent in floating point format in a big endian sequence and was processed as such. This was read into LabVIEW periodically, processed and displayed on the control panel as well as logged to the data file in LabVIEW's **T**echnical **D**ata **M**anagement **S**treaming (TDMS) format.

Offline write commands were conducted by the second state machine on receipt of a signal from the dynamometer controller indicating a ready for transmission mode. The write command was prompted by a user input action on the front panel of the user interface such as a request for access or change of dynamometer mode. In each instance the command sent to the dynamometer was followed by a check state request to ensure the command had been correctly carried out.

The third state machine administered the processing of all data received during an offline read procedure. The state initiator in this case was a "start of transmissions" byte sent from the X-act controller. Data read in appeared in the SCPI syntax and was processed accordingly. This data was then passed on to the applicable indicators as well as being logged to file.

Flow diagrams for each of the communications protocols required for interaction with the dynamometer controller are presented in Figure_ B-2, Figure_ B-3 and Figure_ B-4. These lay out the step by step process required for each transmit/ receive sequence.

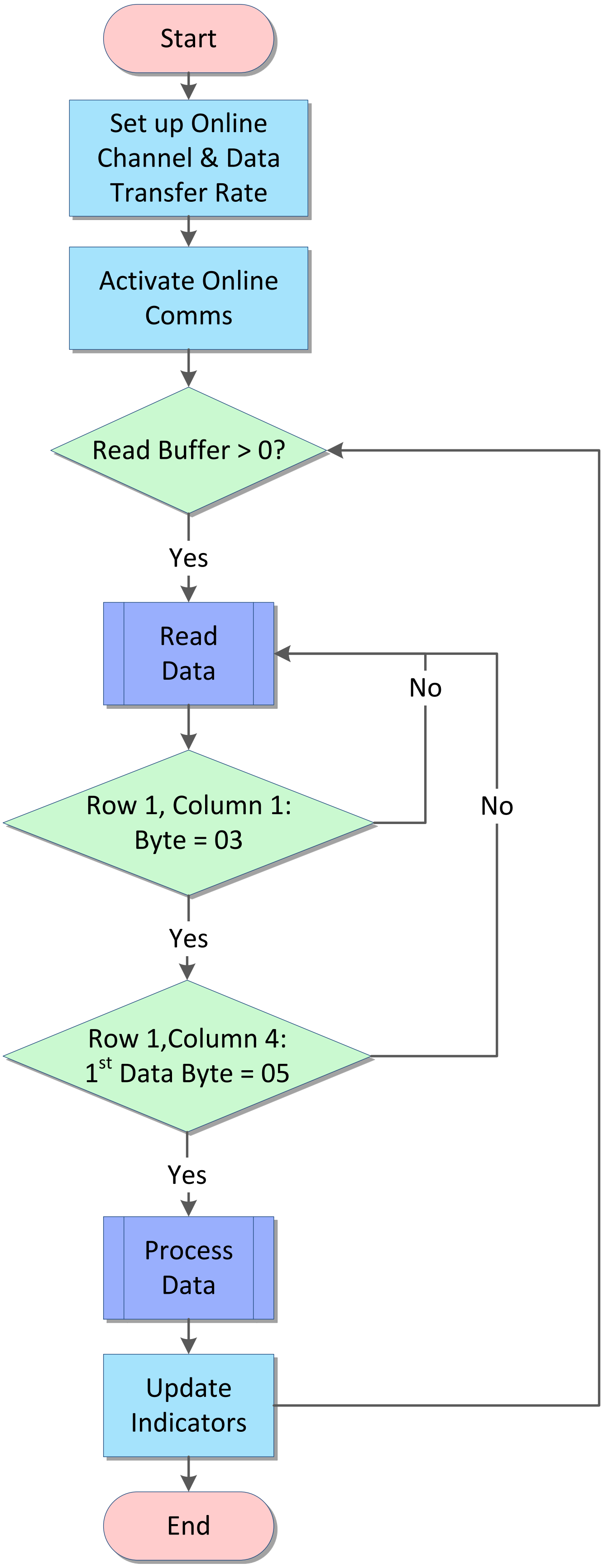


Figure_ B-2: Flow diagram for online data read from dynamometer

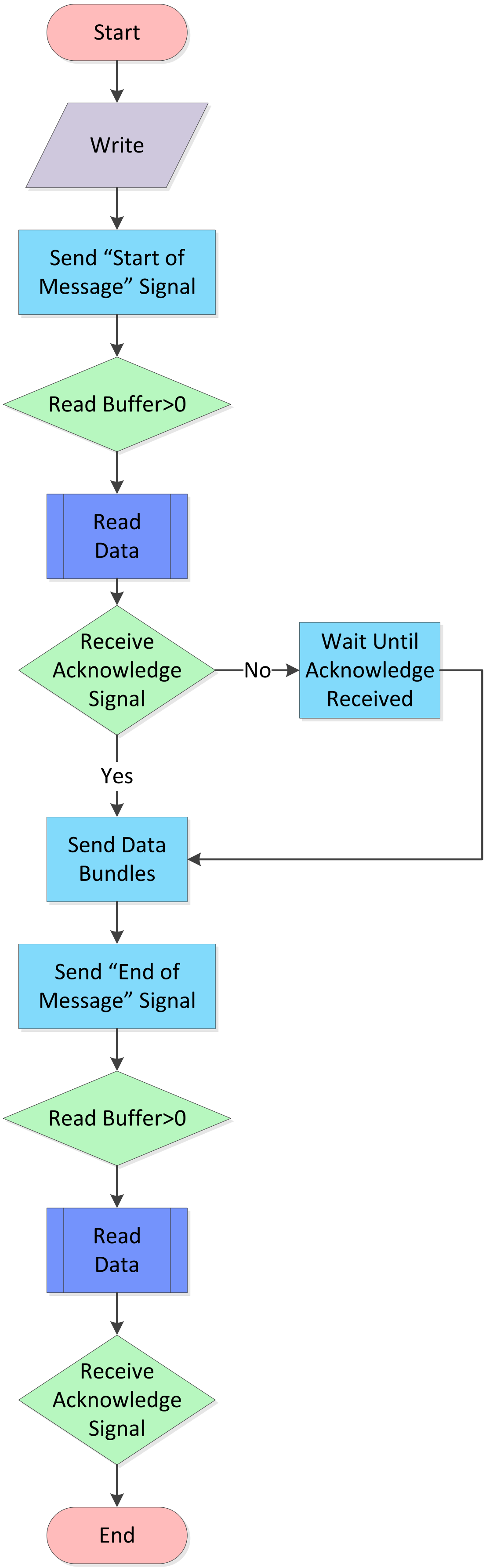


Figure_ B-3: Flow diagram for offline data transmission to dynamometer

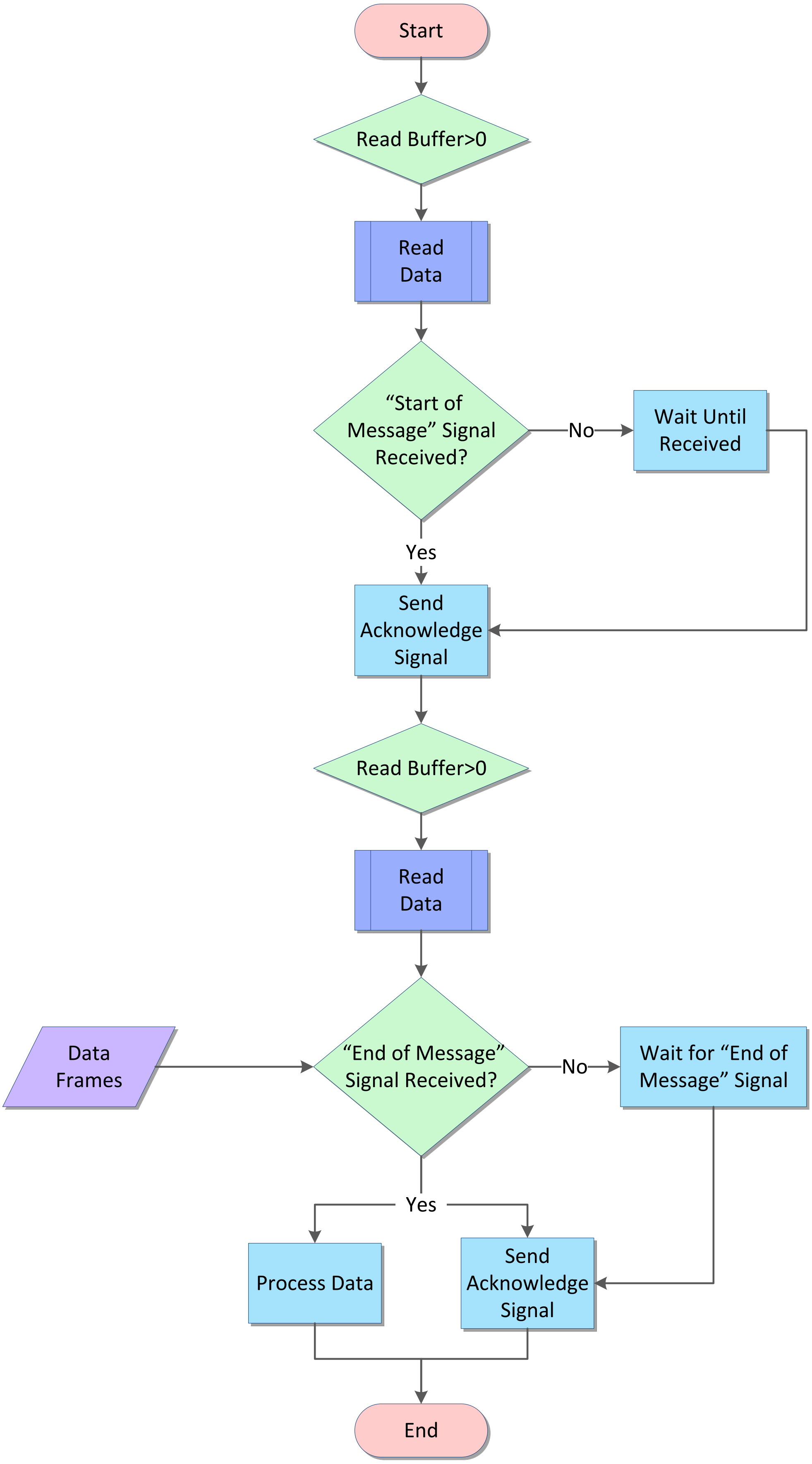
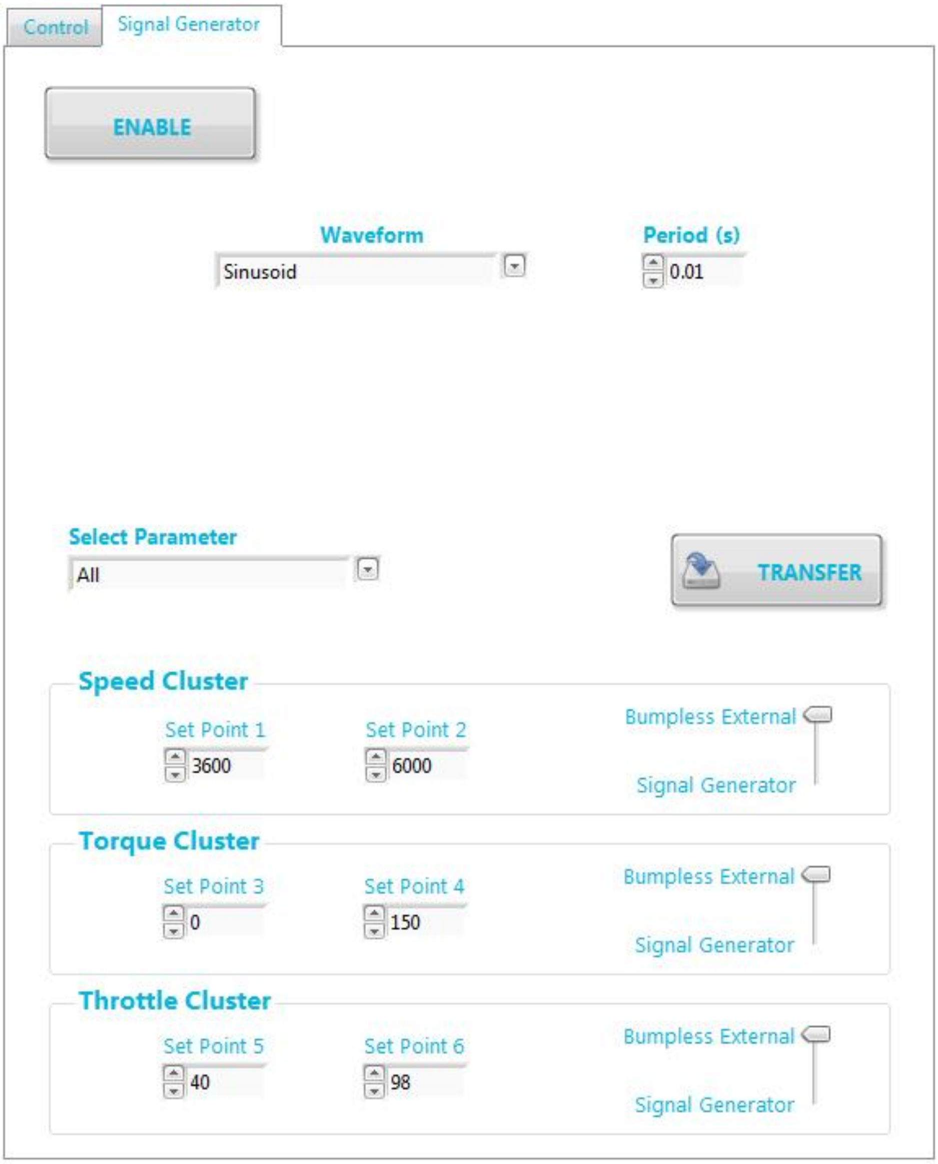


Figure_ B-4: Flow diagram for offline data read from dynamometer

1.4. Signal Generator

Frequency testing of the gas turbine, linear actuator and dynamometer was a necessary foundation to be built, upon which Phase II of the project could be built. As mentioned in Section 5.4.3, sinusoidal signals needed to be generated as inputs to these systems such that system identification could be carried out.

Code was therefore created in the LabVIEW application to facilitate communication with the Schenck X-act controller's signal generator. The operator interacts with the signal generator via a similarly labelled sub-tab in the "Dynamometer" section of the graphic user interface. Using the given controls it was made possible for the user to choose the waveform to be output -options included a ramp, square or sinusoidal waveform. The period of the chosen waveform could be altered within the range from 0.01ms to 600ms. Other permitted modifications were the selection of the set points and control state for the torque, speed and throttle parameters.



Waveform: Sinusoid

Period (s): 0.01

Select Parameter: All

Speed Cluster
Set Point 1: 3600
Set Point 2: 6000

Torque Cluster
Set Point 3: 0
Set Point 4: 150

Throttle Cluster
Set Point 5: 40
Set Point 6: 98

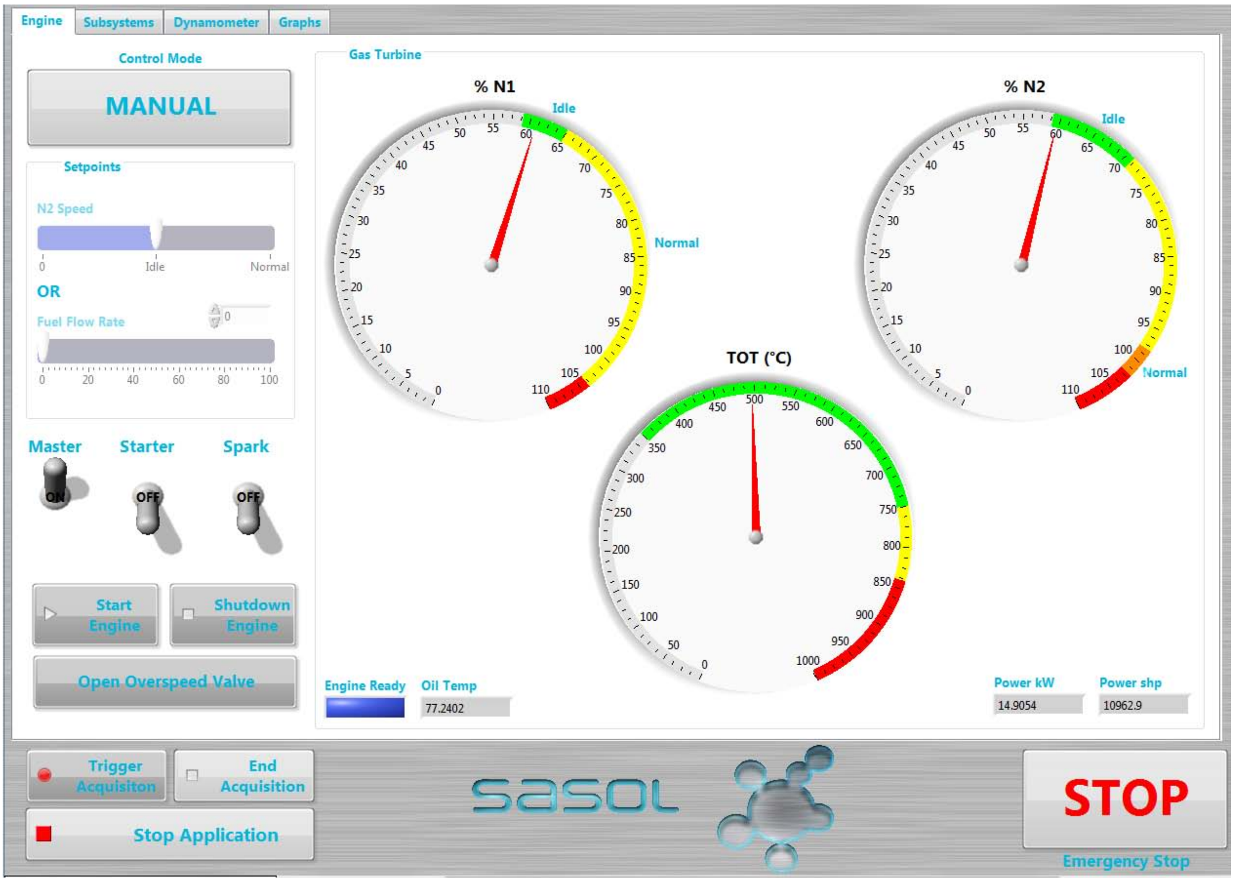
Figure_ B-5: Screenshot of signal generator control console of GUI

2. Turbine Control

ETA was the program originally used to monitor and log all incoming data from the T63. ETA was run from a computer running a Pentium IV processor connected via Ethernet to an Allen Bradley PLC which performed some signal smoothing before relaying the sensor and actuation signals to their targets. The system is pictured on the far right of Figure 40 of Section 5.4.1. The Schenck X-act controller was formerly connected to this computer via a first generation National Instruments PCI CAN card which the user could interface with using ETA. As discussed in Section 5.3.1 the throttle actuator installed could be controlled through use of this same X-act controller. Functionality for communication of the throttle set point was pre-programmed into ETA. Automation of the gas turbine was first accomplished using the ETA software package to communicate to both the dynamometer and throttle actuator thereby controlling both the speed of the output shaft of the T63 and the fuel flow to the engine. The optimum sequence and timing for automation were determined in this manner. Access to the ETA source code was not possible however and thus certain features necessary for future work planned could not be implemented using this software. LabVIEW was used to develop a control system to replace ETA. ETA was however kept on as a redundant system to decrease processor load on each of the host computers and serve as a backup system.

LabVIEW was an advantageous option due to the flexibility afforded by its utilisation and the ability to alter the hard code at any point. The integrated I/O capabilities of this software package allowed seamless integration with the selected sensors. Future testing to be carried out on the engine required manipulation of the fuel supply to the engine, for this reason the system was to enable testing such that a fuel control law could be synthesised for the engine (refer to Appendix C). This required frequency testing of the engine and the inclusion of the signal generator as discussed in Section 5.4.3.

The LabVIEW code was composed to allow user interaction with the system and monitor engine and subsystem operations. A graphic user interface was provided to permit the user to manipulate parameters such as the output speed, dynamometer torque and fuel flow to the engine. Gas turbine and subsystem variables were displayed as on screen indicators as shown in Figure 47. In the case of any operating limits being approached a visual warning was the first indicator to be given. If no corrective action was taken by the user the programme was set to automatically decrease fuel to the engine by bringing down the throttle set point. In the event of the operating limit in question being breached fuel to the gas turbine would immediately be cut off at the fuel nozzle. The code handling the safety related control was contained within a loop given the highest priority ranking, hence when activated commands from these loops took precedence over all other routines. This code was deployed directly onto the real time processor of the NI CompactRIO, meaning that each of the procedures written to limit temperature or speed of the gas turbine ran in parallel, feeding their results along with the user’s demands to a minimum select switch. At this point the lowest fuel flow rate would be passed on to be implemented.



Control Mode: MANUAL

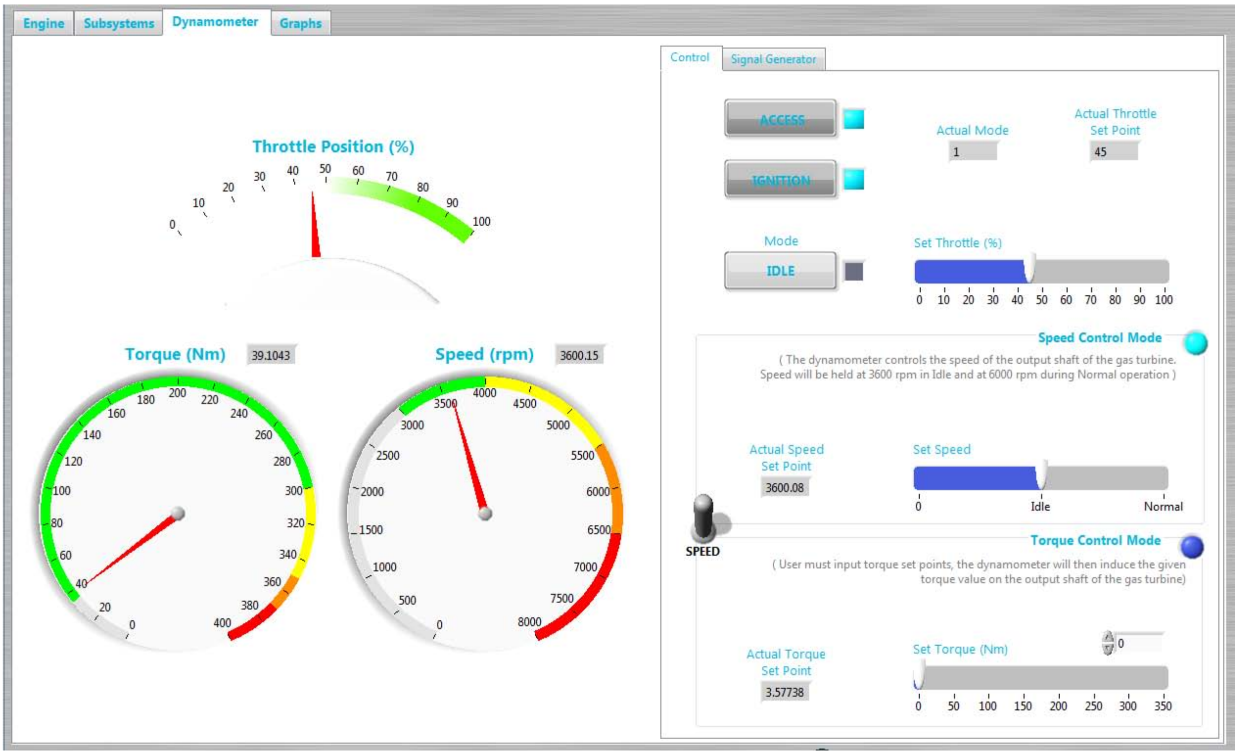
Oil Temp: 77.2402

Power kW: 14.9054

Power shp: 10962.9

Figure_ B-6: Main engine tab LabVIEW user interface

In both software packages the dynamometer could be run in one of two modes, the first being torque/speed control mode in which the dynamometer would apply a given load on the output shaft of the gas turbine. A second, potentially safer way of running the dynamometer was in speed/throttle mode. When operating in this mode the speed set point activated on the dynamometer was held as the maximum speed at which the gas turbine output shaft could spin. Once maximum speed was reached the dynamometer would then apply a resistive load in opposition to the direction of rotation of the power take off shaft of the T63. In this way the maximum speed of the N2 power turbine could be controlled as it was geared directly to the output shaft. The controls and indicators of the dynamometer tab of the LabVIEW user interface are pictured in Figure 48.



Torque (Nm) 39.1043

Speed (rpm) 3600.15

Actual Mode 1

Actual Throttle Set Point 45

Speed Control Mode

(The dynamometer controls the speed of the output shaft of the gas turbine. Speed will be held at 3600 rpm in Idle and at 6000 rpm during Normal operation)

Actual Speed Set Point 3600.08

Torque Control Mode

(User must input torque set points, the dynamometer will then induce the given torque value on the output shaft of the gas turbine)

Actual Torque Set Point 3.57738

Set Torque (Nm) 0

Figure_ B-7: Dynamometer tab of LabVIEW user interface

An automation sequence was created that could be activated at the push of a button. Depression of the “Start Engine” control initiated a command chain that turned the engine master switch, igniter and starter motor on and off. This series of automated commands also set up and directed the dynamometer to ramp up the speed and throttle set points while monitoring check point indicators. The sequence concluded with the illumination of the “Engine Ready” light once the gas turbine had reached flight idle mode. The desired test procedure could then be entered into at this time. On cessation of testing the operator need only depress the “Shutdown Engine” control to stimulate the dynamometer to ramp down the throttle and speed set points and shut off the engine relays. All necessary checks and safety procedures were included in these sub routines. The flow diagrams in Figure_ B-8 and Figure_ B-9 respectively, lay out the step by step procedure followed for automatic start up and shutdown.

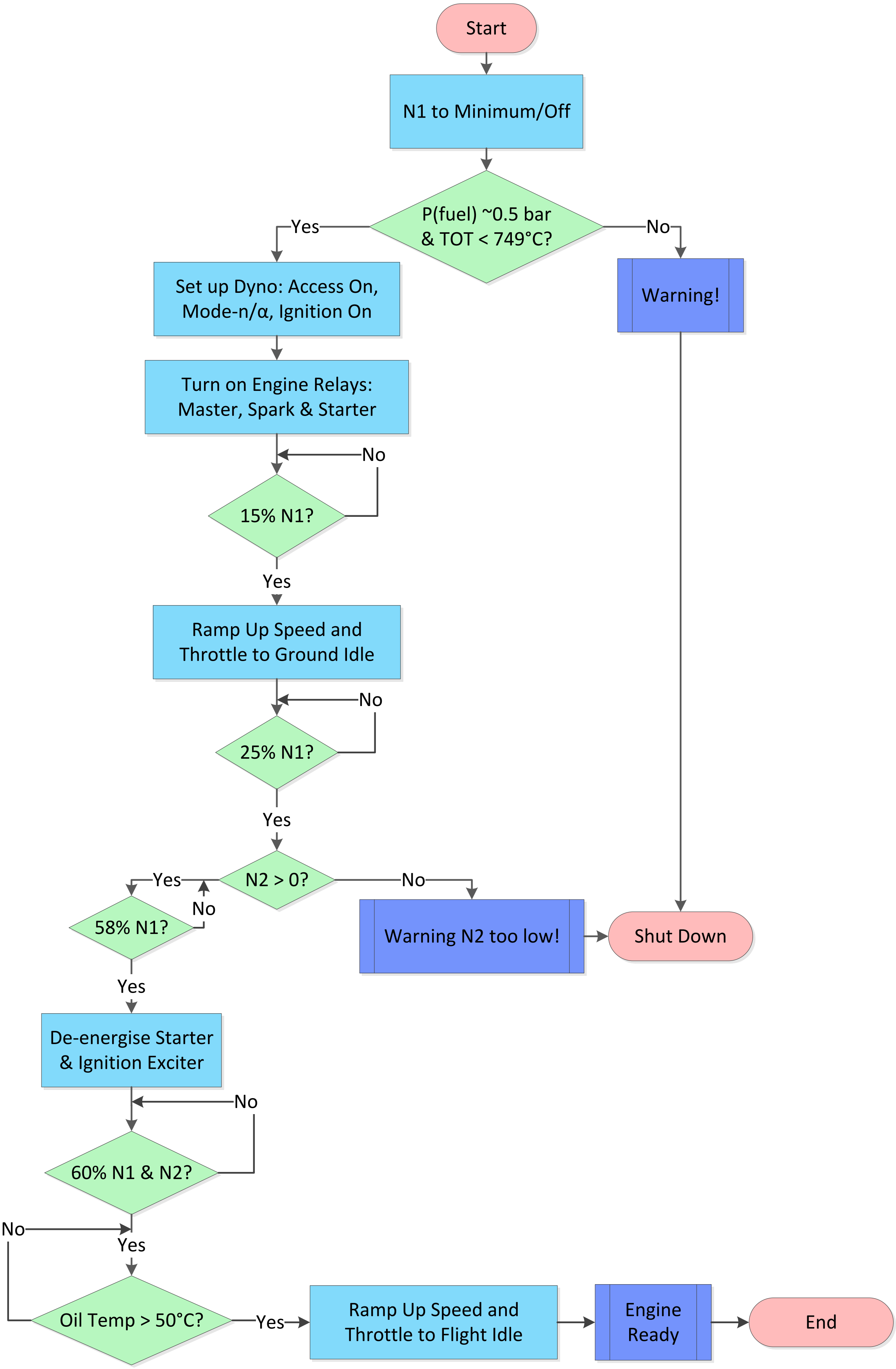


Figure_ B-8: Flow diagram for start-up sequence

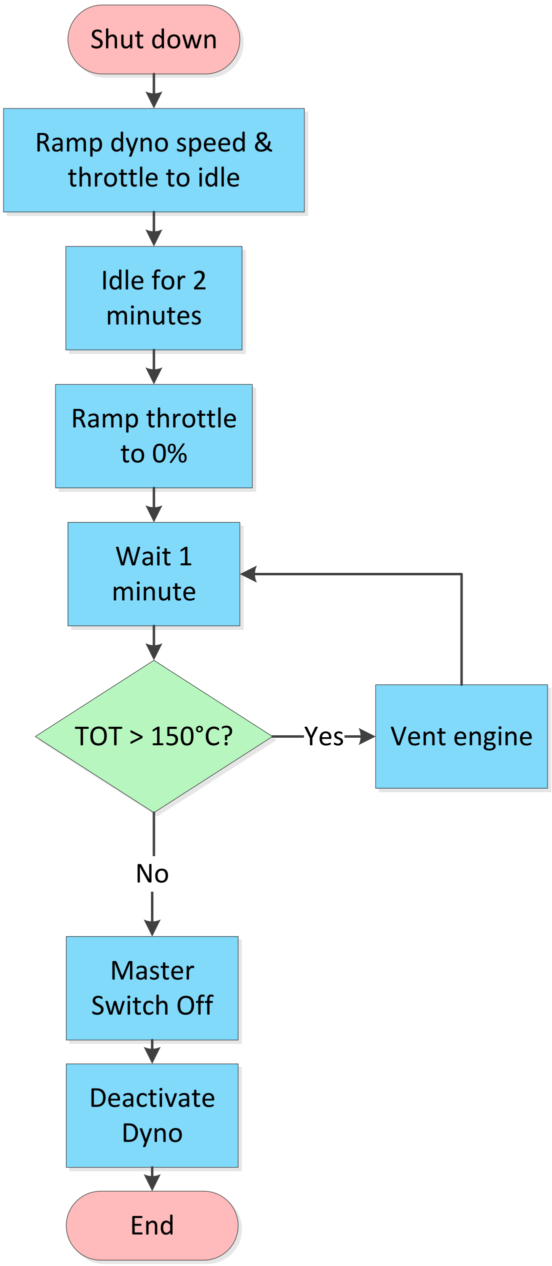


Figure_ B-9: Flow Diagram for shut down sequence

2.1. Data Acquisition and Logging

Each of the two software systems was set up with an independent data logging system. ETA handled data input from a number of fluid supply systems, sensors and from the gas turbine. This data was recorded as a tabular plain text file, with values separated by commas and saved under the project folder within ETA.

LabVIEW was committed to archiving the gas turbine spool speeds, turbine outlet temperature, exhaust gas temperature, control relevant fluid supply information and all data acquired from the dynamometer. The real time processor of the CompactRIO performed the tasks associated with data acquisition and logging. Samples were acquired every 100ms and written to the CompactRIO’s hard drive. The files were recorded in LabVIEW’s TDMS format. The hierarchy of data saved in this format was inherent, making it easily searchable. The TDMS file format was binary based and therefore it possessed a small footprint when saved to disk, 6.88kB/s were recorded when saving 32 channels of information. At this rate the 2GB hard drive of the CompactRIO would take a total of just below 85 hours to fill completely. Due to the fact that TDMS was binary based the format also had a high suitability for transfer via high speed streaming – a peak streaming rate of 3.3MB/s [58] was possible.

The diagram in Figure_ B-10 shows the data logging procedure. Data was to be logged at the request of the user by clicking the "Trigger Acquisition" button on the bottom left of the user interface. Once activated the TDMS file was to be initiated after a check to ensure the folders were not already in existence. If less than 80% of disk space was available, data streaming rates would be slowed thus the minimum free hard drive space was set to 60%. A second check was carried out to determine whether at least this amount of disk space was available. In the case of disk space being lower than the proposed amount the "Low Disk Space" indicator would be illuminated, an error message would be sent and logging would not commence. If sufficient space was at hand, data from the I/O modules as well as that from the dynamometer was stored in three data buffers. Every 100 milliseconds the data from these buffers was written to disk. This process would continue until such time as the operator pressed the "End Acquisition" control and halted all data logging. The files were then transferred, using **F**ile **T**ransfer **P**rotocol (FTP), to a designated folder on the host computer and deleted from the hard drive of the CompactRIO. A multi-threaded FTP server was installed on the host computer and configured to access the "LabVIEW Data\Test Log" directory with permission to list, read or write files. The operator was to must make sure that this server was running before attempting to run the LabVIEW VI's.

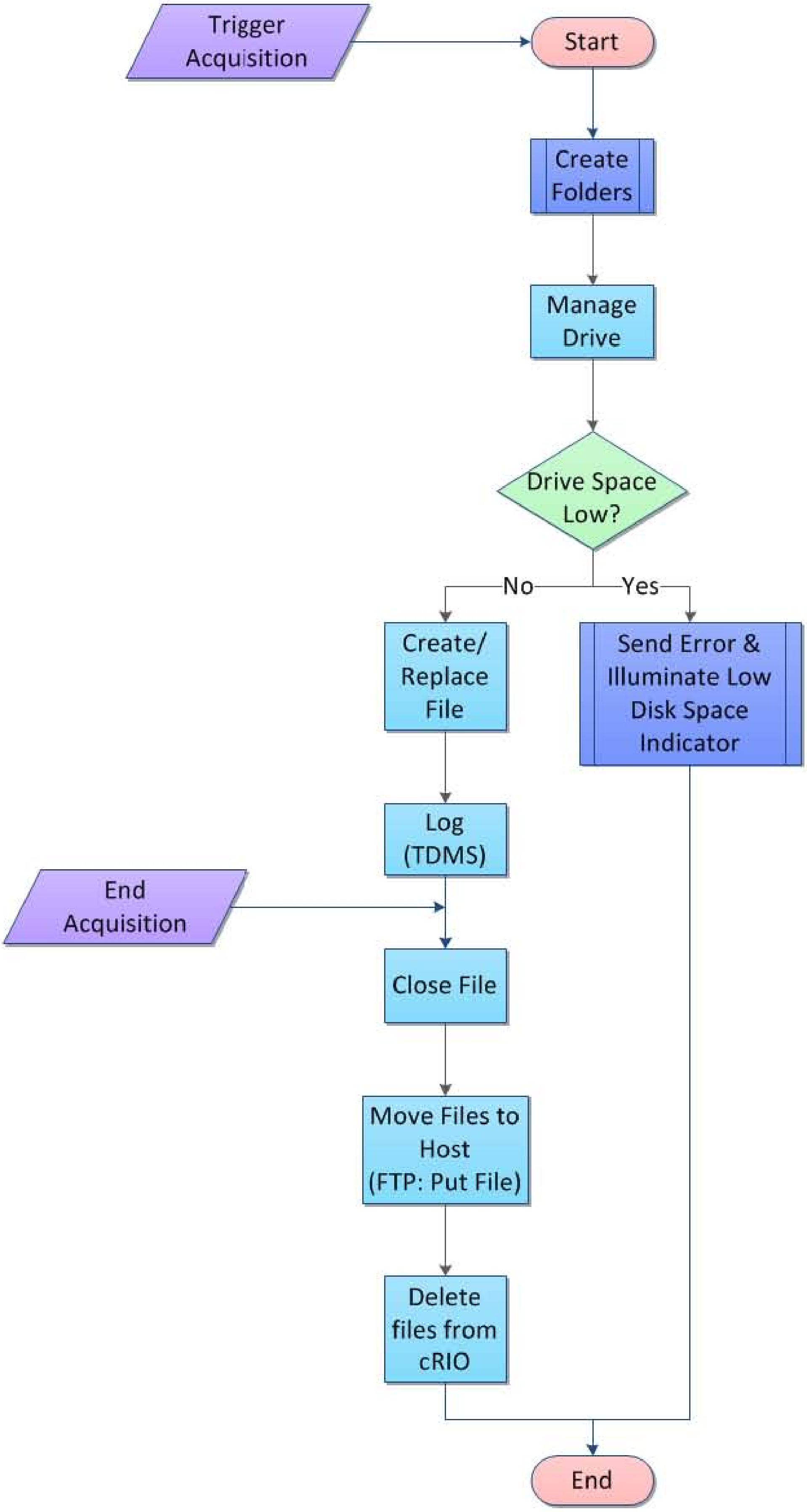


Figure_ B-10: Flow diagram for data logging process

2.2. Inter Target Communications

The following section deals specifically with the existing requirement for commands issued by the operator to be delivered to the real time target. This demand was met via implementation of two producer/consumer loops and inter-target communications that allowed data to be sent from the LabVIEW user interface on the host computer to the real time processor of the CompactRIO.

Activation of certain controls in the user interface caused the event handling loop, the producer, of the host VI to add an element to a command queue. Each element of this queue was then read out on a first-in-first-out basis into the user interface Command Sender, the consumer. A network steam was utilised to transmit packages from the host VI to the CompactRIO. Messages dispatched in this way were picked up by the Command Parser loop on the real-time VI. The Command Parser then enqueued these commands before passing them on to the Message Handling loop of the same VI. From this point the commands were dequeued and distributed to the appropriate process. This provided a lossless means of one-way communication with high throughput capabilities, ideal for commands such as those used to trigger and end acquisition as well as to simultaneously end all applications.

Appendix C:

Specifications

Specifications

Contents

List of Tables

1. Specifications & Justification Thereof

Table_ C-1: User Requirements and Wishes

No.	Description	Desired	Achieved	Demand/ Wish	Rev	Ref
1	Functions and Features					
1.1	Reconfigurable	Yes	Yes	W	0	B.2.2
1.2	Accuracy	< 0.5%	**Cori Flow** = 0.2% **LFM 2003** ≤ 0.3%	W	0	B.2.2
1.3	Repeatability	Yes	Yes	D	0	B.2.2
1.4	Manual Override	Yes	Yes	D	0	B.2.2.3
1.5	User Interface	LabVIEW	Yes	D	0	B.2.2.4
1.6	Automatic Start Up	Yes	Yes	W	0	B.2.2.5
1.7	Full Control of Fuel Flow rates	Yes	Yes	D	0	B.2.2.6
2	Environmental Specifications					
2.1	Multi-Fuel Compatibility	Yes	Yes	D	0	B2.1.4
2.2	Operating Temperature Range	In Test Cell: 0 C to 40°C If Exposed to Combustion Chamber:: 0 C to 750°C	**Cori Flow**- 70°C **LFM 2003**- 50°C **Swagelok Series 141 &142**– 65°C **MAC 900 Series-** 50°C **Swagelok 130 Series**– 93°C	D	0	B.2.1.2
2.3	Supply Voltage	5V/12V/24V/220V	24V/220V	W	0	B.2.1.3
2.4	Protection Rating	Fluid Leak Protection	**Cori Flow**- IP65 **LFM 2003**- IP44. **Swagelok Series 141 &142** – IP66	D	0	B.2.1.1

1.1. Defined Functions and Features

1.1.1. Reconfigurable

The entire control unit was to be reconfigurable to allow for changes and upgrades that may be made in the future. For this reason it was strongly recommended that National Instruments (NI) equipment and software be used wherever possible. SAFL staff and students are well acquainted with and have good baseline knowledge of the NI systems. This means information and project changeover would be less complicated. The NI data acquisition devices are highly modular allowing for easy re-configurability.

1.1.2. Accuracy and Repeatability

A high degree of accuracy and repeatability were required from the device. This ensures reliable operation from the mechanical and electro-mechanical devices as well as making it possible to acquire dependable data and results.

1.1.3. Manual Override Function

This function ensures safety of users and bystanders as well as of the equipment itself in the case of accidents. Manual override was to cause the halt of any on-going procedure and preferably completely shut off power and/or fuel to the various devices at the user's request.

1.1.4. LabVIEW User Interface

(See 1.1.1 of this Appendix)

1.1.5. Automatic Start Up

It was desirable to build in an automatic start up function for the T63 gas turbine. Due to the highly repetitious nature of the mechanical and analytical operations undertaken during each start up sequence it would be highly advantageous to automate the procedure. Handover of the test cell rig to another user would also be a more simple and easy duty.

1.1.6. Full Flow Rate Control

The engine installed at SAFL was used for research purposes involving the characterisation of various types of jet fuel- both conventional and alternate. Full characterisation of these fuels and their effect on engine performance would be greatly improved by the creation of a controller that permitted comprehensive control of the fuel flow rates to the combustion chamber.

1.2. Environmental Specifications

1.2.1. Sealed Housing

The control system was to be located in a test cell and adjoining control room situated in the Sasol Advanced Fuels Laboratory at UCT. Fuel, water and oil are used within the test cell and engine itself thus leaks and spills of these liquids were a possibility. To ensure the device does not become damaged by accidental water or fuel splashes the system was to be sealed against entry of these substances.

1.2.2. Operating Temperature

Electrical devices function best at certain temperatures, it was to be ensured that operation of the unit would be satisfactory and for the given temperature range. Any equipment located within the test cell should be capable of operating at the given temperatures. Operating temperatures near certain parts of the engine, can reach temperatures of up to 750°C therefore parts of the device to be mounted within this area must be capable of withstanding this heat or must be shielded to prevent damage from occurring.

1.2.3. Power Supply

Devices available to supply power to the ECU and each of its electro-mechanical components are as follows:

• Mains	220V	60Hz	(accessible in both areas)
• Battery	+24V	500A	(located within test cell)

• PLC PSU	+24V	20A	(located within control room)
• PSU	+5V	7A	(located within control room)

It was requested that these existing devices be used where possible.

1.2.4. Multiple Fuel Compatibility

The T63 engine is used to test a number of different jet fuels, for this reason all components of the control device must be compatible with the various fuels that may pass through them. Grade 316 stainless steel should be used for all components that come into direct contact with the fuel while seals in these locations should be made from Viton. Components not compatible with the fuels and are not required to come into direct contact with these fuels must be sealed off from accidental contact (see 1.2.1 of this Appendix).

Table_ C-2: Performance Requirements

No.	Description	Desired	Achieved	Demand/ Wish	Rev	Ref
5	**Performance Specifications**					
5.1	Pressure	Up to 40 bar	**Cori Flow**– ~41bar (600psi) **BADGER**– ~41bar (600psi)	D	0	1.5.1
5.2	Flow Range	~0-100 kg/hr	**Cori Flow**– 2 to 100kg/hr **BADGER**– 2 to 100kg/hr	D	0	1.5.2
5.3	Actuation Time	Safety Related ≤ 150 ms	**LFM 2003-** ~100mm/100ms **Swagelok Series 141 &142**– 90° in 2.5s **MAC 900 Series:** Energise- 8ms De-energise- 10ms	W	0	1.5.3
5.4	Sampling Frequency	≥ 5 Hz	10 Hz	W	0	1.5.4

1.3. Performance Requirements

1.3.1. Pressure Rating

The T63's high pressure fuel pump outputs fuel at a maximum pressure of 40 bar at up to 500 kg/hr flow rates. Components to be located in the fuel lines after this high pressure pump must be capable of handling this pressure.

1.3.2. Flow Rate

The mechanical governing system currently routes fuel to the nozzle at a maximum flow rate of up to 100 kg/hr. The electro- mechanical equivalent would need to match this in order to provide the same functionality.

1.3.3. Actuation Time

In the event of an unexpected mishap requiring emergency shutdown of the engine the response time of any devices involved with precipitating this effect should be appropriately short. The current system has a shut off valve that must be activated by the operator. Average response time of a human operator has been recorded as 223 ms [49]. Electro-mechanical actuators are prevalent with actuation rates below 150 ms [59]. An improvement upon the current figure is desirable, preferably below the realistically achievable 150 ms benchmark.

1.3.4. Sampling Frequency

Minimum sampling frequency of the system should be at least twice the maximum frequency input of the system. This is based on the Nyquist Rate (see Section 2.5.5) and the time constant of the engine, which is greater than 0.4 ms [21]. Substituting into Equation (i) gives:

$$f_{sampled} \geq 2f_{input}$$

$$f_{sampled} \geq 2(2.5)$$

$$f_{sampled} \geq 5\ Hz$$

1.4. ECU Specifications

Table_ C-3: List of specifications for ECU

No.	Element	Description
	SPECIFICATIONS OF PRIMARY SYSTEM	
1	**Host Machine**	
1.1	Processor	Intel i7-3770
1.2	Core Operating Frequency (Max)	3.4 GHz
1.3	Flash ROM	1 TB
1.4	RAM	8 GB
1.5	Operating System	Microsoft Windows 7
1.6	Software	National Instruments LabVIEW
2	**Programmable Automation Controller (NI CompactRIO 9014)**	
2.1	Microprocessor	PowerPC 5000 (Freescale MPC5200)
2.2	Core Operating Frequency (Max)	400 MHz
2.2	Flash ROM	2GB
2.3	RAM	128MB
2.4	ADC	10 bit -8channel
2.5	Operating System	Wind River VxWorks 6.3
2.6	Operating Temperature	-40 to 70°C
2.7	Power Supply	9-35V DC (24V Recommended)
2.8	Chassis: NI cRIO-9118	8-Slot, Virtex-5 LX110 (FPGA)
2.9	Modules:	
2.9.1	NI cRIO-9203	8-Channel, ±20 mA, 16-Bit Analog Input
2.9.2	NI cRIO-9205	32-Channel, ±200 mV to ±10 V, 16-Bit Analog Input
2.9.3	NI cRIO-9213	16-Channel Thermocouple Input
2.9.4	NI cRIO-9264	16-Channel, ±10 V, 16-Bit Analog Voltage Output
2.9.5	NI cRIO-9265	4-Channel, 0–20 mA, 16-Bit Analog Current Output
2.9.6	NI cRIO-9472	8-Channel Digital Output
2.9.7	NI cRIO-9477	32-Channel, 0–60 V, Sinking Digital Output
	Inputs & Outputs	
2.10	Analogue Inputs	
2.10.1	Fuel Flow Rate	Coriolis Flow Meter
2.10.2	N1 & N2 Speeds	2 x Tachometers
2.10.3	TOT	Thermocouple Harness
2.10.4	N1 & N2 Lever Angle	2 x Potentiometers
2.10.5	Pressure: Oil, PTO Oil, Torque & Compressor Discharge	Pressure Transducers
2.11	Temperature Sensor Inputs	
2.11.1	Ambient Temperature	J-type Thermocouple
2.11.2	Engine Oil Temperature	J-type Thermocouple
2.11.3	Cooled Oil Temperature	J-type Thermocouple
2.11.4	Exhaust Gas Temperature	J-type Thermocouple
2.12	Analogue Outputs	
2.12.1	Fuel Flow Rate	Coriolis Flow Meter
2.13	Digital Outputs	
2.13.1	Changeover Valve 1a	Relay

2.13.2	Changeover Valve 1b	Relay
2.13.3	Changeover Valve 1c	Relay
2.13.4	Changeover Valve 2a	Relay
2.13.5	Changeover Valve 2b	Relay
2.13.6	Changeover Valve 2c	Relay
2.13.7	Changeover Valve 3a	Relay
2.13.8	Changeover Valve 3b	Relay
2.13.9	Changeover Valve 3c	Relay
2.13.10	Overspeed Valve	Relay
2.13.11	Engine Master Switch	Relay
2.13.12	Engine Spark Switch	Relay
2.13.13	Engine Starter Switch	Relay
3	**System Features**	
3.1	Auto-Start & Shutdown	
3.2	Manual Override	
3.3	Limit Enforcement	
3.4	Serial/Network Communication	RS 232/CAN/Ethernet
3.5	Solenoid Actuated Valves	
3.5.1	Changeover Valve	SS-42GXS4-41ACXE
3.5.2	2 x Changeover Valve	SS-43GXS8MM-42ACXE
3.5.3	Overspeed Valve	SS-42GS4-31OE
3.6	2 x Frequency Converters	T2PR-2255B2
	Fuel Metering	
3.7	Cori Flow M54-AGD-55-0-S	
3.7.1	Power Supply	+15-24V DC
3.7.2	Protection Rating	IP65
3.7.3	Operating Temperature	-45 to 70°C
3.7.4	Pressure	~41 bar (600 psi)
3.7.5	Flow Range	2-100 kg/hr
3.7.6	Accuracy	0.2%
3.7.7	Input signal	RS-232/4-20 mA
3.7.8	Output signal	4-20 mA
3.8	BADGER RC200	
3.8.1	Protection Rating	IP65
3.8.2	Operating Temperature	-40 to 85°C
3.8.3	Pressure	~41 bar (600 psi)
3.8.4	Flow Range	2-100 kg/hr
3.8.5	Input signal	4-20 mA
3.8.6	Output signal	0.2 to 1 bar
3.8.7	Activator	TEIP11
4	**Schenck Systems**	
4.1	X-Act Controller	
4.1.1	Service Interface	RS-232
4.1.2	Remote Interface	CAN
4.1.3	Asynchronous Protocol	ASCII based, SCPI Syntax
4.1.4	Synchronous Protocol	Binary IEEE floating point format
4.1.5	Selectable Units	
4.1.5.1	Speed	rad/sec, U/min
4.1.5.2	Torque	Nm, kNm, lbft
4.1.5.3	Power	W, kW, PS, HP

4.1.5.4	Throttle	1, %
4.1.5.5	Frequency	1/sec, Hz
4.1.5.6	Time	sec
4.2	Dynamometer	W3 S480
4.2.1	Max Power	480 kW
4.2.2	Max Speed	13000 RPM
4.2.3	Max Torque	750 Nm
4.2.4	Moment of Inertia	0.465 kg.m^2
Throttle Position Control Unit		
4.3	Control & Power Unit	LFE 2003
4.3.1	Power Supply	230V AC
4.3.2	Input Signal	0-20 mA
4.3.3	Output Signal	0-10V (0-100 %)
4.4	Actuator	LFM 2003
4.4.1	Nominal Force	220 N
4.4.2	Positioning Motion	Linear & Rotating
4.4.3	Total Stroke	120 mm or 270°
4.4.4	Positioning Deviation	≤ 0.3%
4.4.5	Positioning Time	100 ms (100 mm with 200N resistance)
4.4.6	Max Ambient Temp	50 °
4.4.7	Protection Rating	IP 44

Appendix E:

Standard Operating Procedures

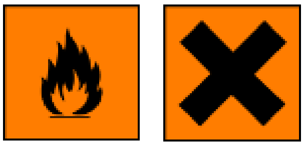
Standard Operating Procedures

1. Manual Operating Procedure

University of Cape Town
Sasol Advanced Fuels Laboratory

OPERATING PROCEDURE:

BE AWARE OF RISKS PERTAINING TO TASK



Procedure number:	
Procedure Description:	**Manual operating procedure for T63 gas turbine**
Procedure compiled by:	Leanne Robertson
Procedure revision date:	30 August 2012
Procedure approved by:	
Nature of revision:	To include changes made in operating procedure ☒ To include instrument modifications ☒ Changes made to wording in procedure document ☐ Other:________________________________ ☐
Re-training required:	**Yes** ☐ **No** ☒ (**Comment:** Who exactly is this aimed at? Who requires re-training?)

NAME OF THE PROCEDURE

1. GENERAL

Objective

The standard operating procedure laid out in this document is provided to ensure safe manual operation of the T63-A-700 Gas Turbine.

Scope

The operating procedure described herein details the following:

- pre-start up inspections
- start-up procedures for each of the supporting sub-systems
- start-up procedure for the T63 gas turbine
- procedure for running the gas turbine at full speed under load
- shut down procedure to be followed for the gas turbine
- shut down procedures for each of the supporting sub-systems

Operating limits of the gas turbine are also specified.

References

- Rolls–Royce Technical Publication: 250–C18 series Operation and Maintenance
- General MSDS for Naphtha, Jet Fuel and Diesel.
- A Test-Cell Installation of a Gas Turbine Engine to Investigate the Performance Advantages of Low Aromatic Fuel; Appendix D- Operational Procedures; Nigel Bester; 2008

2. PRINCIPLE HAZARDS

- Flammable liquids
- Spilling of liquids
- Temperature extremes up to 700°C
- Petroleum products at elevated temperature (hot liquids)

3. PERSONAL PROTECTIVE EQUIPMENT

Closed shoes (safety shoes, or boots) should be worn at all times when in the laboratory and the following additional protective equipment should be worn according to the area in which you are working.

Control Room

Hearing protection during engine operation

Test Cell

Laboratory coat or overall jacket
Safety glasses
Safety gloves (Leather, rubber or latex, depending on application)
NOTE: The test cell may not be entered when the engine is running

Fuel Storage Room

Laboratory coat or overall jacket
Safety glasses

Safety gloves (Leather, rubber or latex, depending on application)

4. FIRST AID AND MEDICAL CARE RELATING TO MSDS: NAPHTHA, DIESEL AND KEROSENE.

Eye contact

Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact

In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash skin thoroughly with soap and water or use recognised skin cleanser. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Inhalation

Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion

Wash out mouth with water. Do not induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention immediately.

Protection of first-aiders

No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Notes to physician

No specific treatment. Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.

Lacerations

Stay Safe. If you are not the victim, practise first aid measures and wear personal protective equipment, latex gloves, safety spectacles, long sleeves.

Control the bleeding before anything else. Putting pressure directly on the laceration while holding it above the level of the heart for 15 minutes should be enough to stop bleeding. Seek medical care; contact medical station immediately/dispatch ambulance.

5. GENERAL PROCEDURE

Apparatus

The Rolls Royce Allison T63-A-700 gas turbine is a turbo shaft engine installed at the Sasol Advanced Fuels Laboratory for use in fuels testing.

Preparation and preventative actions (Pre-start up checks)

Prior to activating any engine sub-systems the following checks must be completed:

- **a.** Check the engine Log Book to ensure all maintenance work is complete and the engine is operational.
- **b.** If maintenance has been performed check that the specific component has been reinstalled and all associated connections made/bolts fastened.
- **c.** Check the floor of the test cell for any loose items that could be ingested by the engine and remove them.
- **d.** Look at the compressor inlet to ensure no foreign objects are present to be ingested. Check the shaft guard and free-wheeling unit for small items of debris.
- **e.** Check all electrical and mechanical sensing lines are secured and unable to be disconnected, burned or ingested by the engine.
- **f.** Ensure all mechanical and electrical connections to the boom box are secure.
- **g.** Ensure the air supply path to the test cell is free of obstructions.

Sub-System Activation

Once the pre-start up checks are complete the various engine subsystems must be activated in the following order, stepping through the individual 'Normal Operation' procedures listed below:

1. Electrical
2. Oil
3. Water
4. Ventilation
5. Fuel

1. **Electrical (Normal Operation)**
    - **a.** Check that all connections to the 24 V power supply (2 x 12 V batteries) in the test cell are secure and that the batteries have sufficient charge by looking at the indicators on their upper surface (indicators should be green if sufficiently charged).
    - **b.** Make sure there are no spilled fluids, especially in close proximity to any electrical wiring.
    - **c.** Ensure that the connections to the starter motor are secured to the engine and the motor is itself secure.
    - **d.** Check the connection to the low tension capacitor discharge ignition exciter is secured as well as the leads connecting to the magnetic chip detectors.
    - **e.** Check the distribution board (DB board) to make sure that all appropriate switches are active.
    - **f.** Open the Programmable Logic Controller (PLC) and in the top left corner switch on breakers 1, 2 and 4.
    - **g.** Switch on the gas turbine controlling computer as well as the dynamometer controller.
    - **h.** Computer System:
        - Open ETA software.
        - Put ETA into “online” mode (green robot icon)
        - In the “Dyno Comms” panel:
            1. Click “Access” button
            2. Check “Access Status” indicator in “Dyno Status” panel turns green
            3. Click “Ignition” button
            4. Check “Ignition Status” indicator in “Dyno Status” panel turns green

2. **Oil (Normal Operation)**
    - **a.** Check the level of oil in both the primary oil tanks by removing the filler caps of each tank. The dip sticks should indicate that the tanks are sufficiently full.
    - **b.** Check that all piping between the oil storage tanks and the engine are properly connected and that there are no disconnected pipes; be sure to check each thermocouple and pressure tapping connections.
    - **c.** Check that the bypass ball valve on the PTO oil line is half way open, if not open to this position.
    - **d.** On the controlling computer:
        1. Switch on the PTO oil pump in the “Supply Relays” panel of ETA.
        2. Wait a moment and ensure that the oil is flowing as intended and make sure the pressure transducer is registering a positive pressure on the controlling computer (~0.5 - 1 bar-gauge).
    - **e.** If the pressure is below 0.5 bar gauge further restrict the oil bypass route by closing the ball valve a small amount, if above 1 bar reduce the restriction as required.

3. **Water (Normal Operation)**
   - **a.** Ensure all pipes within the test cell are secured as desired and unused connections are shut.
   - **b.** Check that the Continuous-Flow Combustion Rig has been isolated via the two shut-off valves, on the right side of its wall mounted control panel.
   - **c.** Switch on the cooling tower fan on the DB board outside the Gas Turbine Control Room. (Optional step dependent on ambient conditions and temperature)
   - **d.** Check that the fan is operational and there is sufficient water in the cooling tower. Open the fresh water supply valve to top up tank if not sufficiently full.
   - **e.** In the pump room:
     1. Fully open shut-off valve A and switch on the cooling tower supply pump (Pump A).
     2. Check that the water tank has fully drained if full.
     3. Fully open shut-off valve B and switch on the test cell supply pump (Pump B).
   - **f.** Check that the pressure gauge within the test cell is registering and for any leaks that may have started.
   - **g.** Monitor the dyno outlet water temperature during operation to ensure the temperature remains below 40°C.

4. **Ventilation (Normal Operation)**
   - **a.** Walk through the test cell and ensure there are no loose items that may be sucked into the ventilation system.
   - **b.** Ensure that there are no blockages in front of the inlet (remove the gas turbine inlet cover if not already done) or exhaust and firmly secure the test cell doors.
   - **c.** Switch on the orange DB board containing the supply and exhaust fan variable speed drives.
   - **d.** Ensure both emergency stop switches are pulled out, located on the orange DB board outside the operating room and on the control box in the control room.
   - **e.** Note the pressure inside the test cell from the ambient pressure transducer.
   - **f.** Dial both the speed indicators to about 20% and start the fans one at a time.
   - **g.** Slowly increase the speed of the fans one by one to attain full ventilation (Full ventilation is reached when one of the fans reaches 100% and the test cell pressure is as it was before the fans were activated).

5. **Fuel (Normal Operation)**
   - **a.** All fittings and piping must be checked to ensure they are all appropriately connected and secure.
   - **b.** The supply and return fuel lines should be attached to the fuel drums to be used and the both of the shut-off valves should be set either to the left or right for the supply from either drum A or B.
   - **c.** The shut-off valve between the fuel filter and the flow meter must be in the open position allowing fuel flow to the test cell and the 3-way valve between the air separation unit and the back pressure regulator must be pointing in the direction of the regulator (i.e. not open to atmosphere).
   - **d.** The 3-way valve between the engine and the emergency shut-off valve must be oriented to enable flow to the engine and not to the purge point. The line must be firmly secured to the fuel inlet on the engine.
   - **e.** On the controlling computer:
     1. Ensure that there is sufficient fuel in the drum by referring to the fuel level indicator in ETA. (The fuel level indicator in the fuel drum often sticks – ensure it is free before commencing operation)
     2. Enable the boost pump by clicking the “Fuel Pump” button on the “Supply Relays” panel in ETA.

3. Click the “Fuel Supply” button on the “Supply Relays” panel in ETA to enable the emergency shut-off valve.

Engine Light-off

It is recommended to read the entire light-off procedure in the maintenance and operations manual to gain a full understanding of all aspects of the engine behaviour. Light-off is a rapid process and the operator must already possess all necessary knowledge.

All the above 'Normal Operation' procedure lists for the various subsystems should have been complete at this stage. The following is the procedure for normal starting of the engine, that is in ambient conditions above 4°C.

T-63 Operating Limits

Temperature limits for T63 installation

Measurement	Upper Limit °C	Lower Limit °C
Engine Stabilised TOT	749	350
Mixed Exhaust Gases	200	None
Engine Oil Out	107	0
PTO Oil Out	107	0
Dyno Water Out	60	1

Speed limits for T63 installation

Measurement	Upper Limit %	Lower Limit %
N_1	104	None
N_2 @ Idle	71	59
N_2 @ Normal Operation	102	98
N_2 @ Loss of Load	120	N/A

Pressure limits for T63 installation

Measurement	Upper Limit (Bar Gauge)	Lower Limit (Bar Gauge)
Engine Oil	8.96	6.21
PTO Oil	1	0.5
Engine Torque Sensor	6.89	2.07
Fuel Supply	0.7	0.4

(Note: PTO = Power Take-Off)

Torque limits for T63 installation

Measurement		Nm	Upper Limit (Bar Gauge)	kW
Torque	Continuous	337	5.86	212
	30 min limit	397	6.89	250
	10 sec limit	434	7.52	273

1. Normal Starting

CAUTION: Our engine incorporates a low energy exciter. Operating time limits are as follows: 2 minutes on, 3 Minutes off; 2 minutes on, 23 minutes off.

CAUTION: If the N2 turbine is not rotating by 25% N1 speed abort the Start. A second or third start attempt may be made; if the Condition still exists refer to Section III, Troubleshooting Table 6, Item 58 of Rolls Royce 250-C18 Series Operation and Maintenance Manual.

The following procedure should be used for all engine starts in the gas turbine test cell:

- **a.** Rotate both N1 and N2 throttle levers to their respective minimum/off positions.
- **b.** Check that the engine fuel supply pressure is reading ~0.5 bar.
- **c.** Ensure the residual TOT be no more than 150°C when light-off is attempted.
- **d.** In ETA on controlling computer:
  1. Turn on “Start Logging” button in toolbar
  2. Switch on the “P_y Bleed” button in the “Supply Relays” panel.
  3. Switch on the “Master”, “Spark” and “Start” buttons on the “Power Relays’ panel
- **e.** On the desk mounted instrument panel: switch on the master and spark switches.
- **f.** Energize the starter and ignition exciter by pressing down the start switch.
- **g.** At 15% N1 rotate the N1 throttle controller to the idle position.
- **h.** In ETA on controlling computer:
  1. Initiate the dynamometer in Commissioning mode
  2. Increase the torque gradually as needed to load the engine such that %N2 drops to 60%.
- **i.** De-energize the starter and ignition exciter when 58% N1 speed is reached by releasing the start switch and switching off the ignite switch. Start is complete when a stable N1 speed of 59 - 65 % is reached.
- **j.** Check that the oil pressure is within limits, if not immediately shut- down.
- **k.** Stabilise engine at these conditions for 1 minute

6. TERMINATING A PROCEDURE

Engine Operation and Shut-down

It is recommended to read the engine operation section of the maintenance and operations manual to gain a full understanding of all aspects of the engine behaviour so as to be able to deal with problems that occur immediately and in the correct manner.

Prior to the addition of load, other than that used to keep the N2 speed at 60%, the N1 governor lever must be advanced to the fully open position.

- **a.** If the engine oil pressure is within limits, and the temperature ≥50°C, as well as all other test cell temperatures and pressures within limits, the N2 governor lever may be slowly advanced to the fully open position.
- **b.** The N1 governor lever may then be slowly advanced to the point where N2 speed reaches 100%.
- **c.** Load can now be slowly applied to the engine, continually checking the N2 speed by trimming with the N1 governor lever.
- **d.** Continually monitor all systems to ensure the engine and all subsystems stay within limits.
- **e.** Once testing is complete return the load to idle load.
- **f.** Bring the engine to idle by rotating the N1 gas producer lever to idle gradually while maintaining N2 speed at 100%.
- **g.** Rotate the power turbine (N2) lever to the minimum position.
- **h.** Trim the load to settle the N2 speed at 60%.
- **i.** Idle the engine for exactly 2 minutes.
- **j.** Rotate the N1 gas producer lever to the off position and monitor the TOT gauge for after fires. In the case of after fires execute step “6k”.
- **k.** If TOT rises above 200°C motor (“vent”) the engine by turning on the “Start” switch till N1 speed reaches 10% (the “Spark” switch must be off during this procedure). Repeat if necessary.
- **l.** Once TOT has dropped to ~150°C the “Master” switch may be turned off.
- **m.** On the controlling computer in ETA turn off the following:
  1. “Master Ignition”, “Starter” and “Spark” in the “Power Relays” panel.

2. Switch off the "P_y Bleed", "Oil Pump", "Fuel Pump" and "Fuel Supply" buttons in the "Supply Relays" panel.
3. Click "Stop Logging' button in toolbar.

7. EMERGENCY SHUT DOWN OF SYSTEM

There are two methods for emergency shutdown. Each of these methods functions independently from the other, thus any one of the two may be used at any point to achieve immediate results.

A. Emergency Engine Shutdown

Rotate the N1 lever to the minimum position and turn off the master switch on the desktop mounted instrument panel.
This will result in the shutoff of both fuel and power to the engine.

B. Emergency Fuel Shutoff Buttons

Two fuel shutoff buttons have been installed. The two large red buttons are located as follows:

- **a.** In the control room near the desktop mounted instrument panel
- **b.** On the wall above the fuel filtering system.

Each of these buttons functions independently and when pressed will cut off fuel to the engine via the solenoid valve located on the inner wall of the test cell.

C. Emergency Idle Mode

A third emergency method is also available in the form of a solenoid valve attached to the P_y pneumatic signal line. Opening this solenoid valve bleeds the air from this line to the atmosphere resulting in the engine dropping into idle mode. The method to achieve this is as follows:

On the controlling computer in ETA:

- **a.** Click the "P_y Vent" button on the "Supply Relays" panel

8. CRITICAL EQUIPMENT LIST

Ensure a spill kit is available for fluid spills
Ensure fire extinguishers are located in the vicinity in the case of fire

9. GENERAL MAINTENANCE

Engine oil should be tested on a regular basis: Oil should be drawn from the system where it exits the engine and sent for analysis. Oil condition should be analysed and an engine wear test carried out on the oil. In the event that laboratory analysis indicates that the oil should be changed then oil in both the PTO and main engine oil tanks must be completely drained and renewed to ensure the engine stays in good working condition. When this oil purge is carried out three oil system checks should also be done. These checks are as follows:

- Remove and clean the oil filter located on the top of the engine (NOTE: a syringe should be used to draw out the oil in this cavity before removing the filter otherwise the dirt from the filter may wash out into the system)

Procedure number:	*Procedure revision date:*

SAFETY OPERATING PROCEDURE BLOCK STRUCTURE:

Job	Job Step	Method	Hazard	Risk	Control Measure	Task observation	
						Task executed effectively	**Deviations noticed**
Sub-System Activation - Electrical	1a	Check that all connections to the 24 V power supply (2 x 12 V batteries) in the test cell are secure	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		
	1b	Make sure there are no spilled fluids, especially in close proximity to any electrical wiring	Slipping Electric shock Exposure	Spilled fluids, Exposed/ broken wires Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	1c	Ensure that the connections to the starter motor are secured to the engine and the motor is itself secure.	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		
	1d	Check the connection to the ignition exciter is secured as well as the leads connecting to the magnetic chip detectors.	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		

	1e	Check the DB board to make sure that all appropriate switches are active.					
	1f	Open the PLC and in the top left corner switch on breakers 1, 2 and 4.					
	1g	Switch on the gas turbine controlling computer as well as the dynamometer controller.					
	1h	Entries on computer System					
Sub-System Activation - Oil	2a	Check the level of oil in both the primary oil tanks by removing the filler caps of each tank. The dip sticks should indicate that the tanks are sufficiently full.	Slipping Exposure	Spilled fluids, Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	2b	Check that all piping between the oil storage tanks and the engine are properly connected and that there are no disconnected pipes; be sure to check each thermocouple and pressure tapping connections.	Slipping Electric shock Exposure	Spilled fluids, Exposed/ broken wires Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		

	2c	Check that the bypass ball valve on the PTO oil line is half way open, if not open to this position.					
	2d	Entries on controlling computer					
	2e	If the pressure is below 0.5 bar gauge further restrict the oil bypass route by closing the ball valve a small amount, if above 1 bar reduce the restriction as required					
Sub-System Activation - Water	3a	Ensure all pipes within the test cell are secured as desired and unused connections are shut.	Slipping Exposure Lacerations	Spilled fluids, Toxic substances Sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	3b	Check that the Continuous-Flow Combustion Rig has been isolated via the two shut-off valves, on the right side of its wall mounted control panel.					
	3c	Switch on the cooling tower fan on the DB					

		board outside the Gas Turbine Control Room.					
	3d	Check that the fan is operational and there is sufficient water in the cooling tower. Open the fresh water supply valve to top up tank if not sufficiently full.					
	3e	Turn on Pumps and Valves A & B in pump room	Slipping	Spilled fluids	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	3f	Check that the pressure gauge within the test cell is registering and for any leaks that may have started.	Slipping	Spilled fluids	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	3g	Monitor the dyno outlet water temperature during operation to ensure the temperature remains below 40°C.					
Sub-System Activation - Ventilation	4a	Walk through the test cell and ensure there are no loose items that may be sucked into the ventilation system.					

	4b	Ensure that there are no blockages in front of the inlet (remove the gas turbine inlet cover if not already done) or exhaust and firmly secure the test cell doors.	Finger Pinch	Door			
	4c	Switch on the orange DB board containing the supply and exhaust fan variable speed drives.					
	4d	Ensure both emergency stop switches are pulled out, located on the orange DB board outside the operating room and on the control box in the control room.					
	4e	Note the pressure inside the test cell from the ambient pressure transducer.					
	4f	Dial both the speed indicators to about 20% and start the fans one at a time.					
	4g	Slowly increase the speed of the fans one					

		by one to attain full ventilation					
Sub-System Activation - Fuel	5a	All fittings and piping must be checked to ensure they are all appropriately connected and secure.	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	5b	The supply and return fuel lines should be attached to the fuel drums to be used and the both of the shut-off valves should be set either to the left or right for the supply from either drum A or B.	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	5c	The shut-off valve between the fuel filter and the flow meter must be in the open position					
	5d	The 3-way valve between the engine and the emergency shut-off valve must be oriented to enable flow to the engine and not to the purge point. The line must be firmly					

		secured to the fuel inlet on the engine.					
	5e	Entries on controlling computer					
Engine Light Off – Normal Start		Sequence of events carried out in control room to start up the gas turbine and achieve operation in idle mode.	Hearing Loss	Gas Turbine Noise	Wear ear protection		
Engine Operation		Sequence of events carried out in control room to operate the gas turbine at varying speeds and loads.	Hearing Loss	Gas Turbine Noise	Wear ear protection		

Deviations noticed:	**Corrective action:**

EQUIPMENT, METHODS AND PROCEDURES CAN NOT BE USED WITHOUT BEING DECLARED COMPETENT BY AN OBSERVER (QUALIFIED PERSON).

Procedure number:	Trainee:	Control Number:	Signature:	Observer:	Control Number:	Signature:	Date:

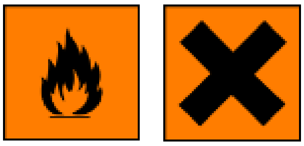
I HEREBY ACKNOWLEDGE RECEIPT OF THE ABOVE-MENTIONED DOCUMENT AND DECLARE THAT I HAVE READ AND UNDERSTAND THE CONTENTS AND THAT I WILL ADHERE TO THIS PROCEDURE/WORK INSTRUCTION DURING THE PERFORMANCE OF MY DUTIES.

2. ETA Automatic Operating Procedure

University of Cape Town
Sasol Advanced Fuels Laboratory

OPERATING PROCEDURE:

BE AWARE OF RISKS PERTAINING TO TASK



Procedure number:	
Procedure Description:	**Operating procedure for T63 gas turbine using ETA Automation**
Procedure compiled by:	Leanne Robertson
Procedure revision date:	15 July 2013
Procedure approved by:	
Nature of revision:	To include changes made in operating procedure ☒ To include instrument modifications ☒ Changes made to wording in procedure document ☐ Other:________________________________ ☐
Re-training required:	**Yes** ☐ **No** ☒ (**Comment:** Who exactly is this aimed at? Who requires re-training?)

NAME OF THE PROCEDURE

10. GENERAL

Objective

The standard operating procedure laid out in this document is provided to ensure safe operation of the T63-A-700 Gas Turbine.

Scope

The operating procedure described herein details the following:

- pre-start up inspections
- start up procedures for each of the supporting sub-systems
- start up procedure for the T63 gas turbine
- shut down procedure to be followed for the gas turbine
- shut down procedures for each of the supporting sub-systems

Operating limits of the gas turbine are also specified.

References

- Rolls–Royce Technical Publication: 250–C18 series Operation and Maintenance
- General MSDS for Naphtha, Jet Fuel and Diesel.
- A Test-Cell Installation of a Gas Turbine Engine to Investigate the Performance Advantages of Low Aromatic Fuel; Appendix D- Operational Procedures; Nigel Bester; 2008

11. PRINCIPLE HAZARDS

- Flammable liquids
- Spilling of liquids
- Temperature extremes up to 700°C
- Petroleum products at elevated temperature (hot liquids)

12. PERSONAL PROTECTIVE EQUIPMENT

Closed shoes (safety shoes, or boots) should be worn at all times when in the laboratory and the following additional protective equipment should be worn according to the area in which you are working.

Control Room

Hearing protection during engine operation

Test Cell

Laboratory coat or overall jacket
Safety glasses
Safety gloves (Leather, rubber or latex, depending on application)
NOTE: The test cell may not be entered when the engine is running

Fuel Storage Room

Laboratory coat or overall jacket
Safety glasses
Safety gloves (Leather, rubber or latex, depending on application)

13. FIRST AID AND MEDICAL CARE RELATING TO MSDS: NAPHTHA, DIESEL AND KEROSENE.

Eye contact

Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact

In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash skin thoroughly with soap and water or use recognised skin cleanser. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Inhalation

Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion

Wash out mouth with water. Do not induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention immediately.

Protection of first-aiders

No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Notes to physician

No specific treatment. Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.

Lacerations

Stay Safe. If you are not the victim, practise first aid measures and wear personal protective equipment, latex gloves, safety spectacles, long sleeves.

Control the bleeding before anything else. Putting pressure directly on the laceration while holding it above the level of the heart for 15 minutes should be enough to stop bleeding. Seek medical care; contact medical station immediately/dispatch ambulance.

14. GENERAL PROCEDURE

Apparatus

The Rolls Royce Allison T63-A-700 gas turbine is a turbo shaft engine installed at the Sasol Advanced Fuels Laboratory for use in fuels testing.

Preparation and preventative actions (Pre-start up checks)

Prior to activating any engine sub-systems the following checks must be completed:

h. Check the engine Log Book to ensure all maintenance work is complete and the engine is operational.
i. If maintenance has been performed check that the specific component has been reinstalled and all associated connections made/bolts fastened.
j. Check the floor of the test cell for any loose items that could be ingested by the engine and remove them.
k. Look at the compressor inlet to ensure no foreign objects are present to be ingested. Check the shaft guard and free-wheeling unit for small items of debris.
l. Check all electrical and mechanical sensing lines are secured and unable to be disconnected, burned or ingested by the engine.
m. Ensure all mechanical and electrical connections to the boom box are secure.
n. Ensure the air supply path to the test cell is free of obstructions.

Sub-System Activation

Once the pre-start up checks are complete the various engine subsystems must be activated in the following order, stepping through the individual 'Normal Operation' procedures listed below:

6. Electrical
7. Oil
8. Water
9. Ventilation
10. Fuel

3. **Electrical (Normal Operation)**
    - **i.** Check that all connections to the 24 V power supply (2 x 12 V batteries) in the test cell are secure and that the batteries have sufficient charge by looking at the indicators on their upper surface (indicators should be green if sufficiently charged).
    - **j.** Make sure there are no spilled fluids, especially in close proximity to any electrical wiring.
    - **k.** Ensure that the connections to the starter motor are secured to the engine and the motor is itself secure.
    - **l.** Check the connection to the low tension capacitor discharge ignition exciter is secured as well as the leads connecting to the magnetic chip detectors.
    - **m.** Check the distribution board (DB board) to make sure that all appropriate switches are active.
    - **n.** Open the Programmable Logic Controller (PLC) and in the top left corner switch on breakers 1, 2 and 4.
    - **o.** Ensure the cable connecting the PCI CAN cards of the X-act controller and ETA host machine is in place.
    - **p.** Switch on the gas turbine controlling computer as well as the dynamometer controller.
    - **q.** Computer System:
        - Open ETA software.
        - Put ETA into “online” mode (green robot icon)

4. **Oil (Normal Operation)**
    - **f.** Check the level of oil in both the primary oil tanks by removing the filler caps of each tank. The dip sticks should indicate that the tanks are sufficiently full.
    - **g.** Check that all piping between the oil storage tanks and the engine are properly connected and that there are no disconnected pipes; be sure to check each thermocouple and pressure tapping connections.
    - **h.** Check that the bypass ball valve on the PTO oil line is half way open, if not open to this position.
    - **i.** On the controlling computer:
        3. Switch on the PTO oil pump in the “Supply Relays” panel of ETA.
        4. Wait a moment and ensure that the oil is flowing as intended and make sure the pressure transducer is registering a positive pressure on the controlling computer (~0.5 - 1 bar-gauge).
    - **j.** If the pressure is below 0.5 bar gauge further restrict the oil bypass route by closing the ball valve a small amount, if above 1 bar reduce the restriction as required.
    - **k.** Switch off the PTO oil pump in the “Supply Relays” panel of ETA.

4. **Water (Normal Operation)**
    - **h.** Ensure all pipes within the test cell are secured as desired and unused connections are shut.
    - **i.** Check that the Continuous-Flow Combustion Rig has been isolated via the two shut-off valves, on the right side of its wall mounted control panel.

- **j.** Switch on the cooling tower fan on the DB board outside the Gas Turbine Control Room. (Optional step dependent on ambient conditions and temperature)
- **k.** Check that the fan is operational and there is sufficient water in the cooling tower. Open the fresh water supply valve to top up tank if not sufficiently full.
- **l.** In the pump room:
    1. Fully open shut-off valve A and switch on the cooling tower supply pump (Pump A).
    2. Check that the water tank has fully drained if full.
    3. Fully open shut-off valve B and switch on the test cell supply pump (Pump B).
- **m.** Check that the pressure gauge within the test cell is registering and for any leaks that may have started.
- **n.** Monitor the dyno outlet water temperature during operation to ensure the temperature remains below 40°C.

6. **Ventilation (Normal Operation)**
    - **h.** Walk through the test cell and ensure there are no loose items that may be sucked into the ventilation system.
    - **i.** Ensure that there are no blockages in front of the inlet (remove the gas turbine inlet cover if not already done) or exhaust and firmly secure the test cell doors.
    - **j.** Switch on the orange DB board containing the supply and exhaust fan variable speed drives.
    - **k.** Ensure both emergency stop switches are pulled out, located on the orange DB board outside the operating room and on the control box in the control room.
    - **l.** Note the pressure inside the test cell from the ambient pressure transducer.
    - **m.** Dial both the speed indicators to about 20% and start the fans one at a time.
    - **n.** Slowly increase the speed of the fans one by one to attain full ventilation (Full ventilation is reached when one of the fans reaches 100% and the test cell pressure is as it was before the fans were activated).

7. **Fuel (Normal Operation)**
    - **f.** All fittings and piping must be checked to ensure they are all appropriately connected and secure.
    - **g.** The supply and return fuel lines should be attached to the fuel drums to be used and the both of the shut-off valves should be set either to the left or right for the supply from either drum A or B.
    - **h.** The shut-off valve between the fuel filter and the flow meter must be in the open position allowing fuel flow to the test cell and the 3-way valve between the air separation unit and the back pressure regulator must be pointing in the direction of the regulator (i.e. not open to atmosphere).
    - **i.** The 3-way valve between the engine and the emergency shut-off valve must be oriented to enable flow to the engine and not to the purge point. The line must be firmly secured to the fuel inlet on the engine.
    - **j.** On the controlling computer:
        1. Ensure that there is sufficient fuel in the drum by referring to the fuel level indicator in ETA. (The fuel level indicator in the fuel drum often sticks – ensure it is free before commencing operation)

Engine Light-off

It is recommended to read the entire light-off procedure in the maintenance and operations manual to gain a full understanding of all aspects of the engine behaviour. Light-off is a rapid process and the operator must already possess all necessary knowledge.

All the above 'Normal Operation' procedure lists for the various subsystems should have been complete at this stage. The following is the procedure for normal starting of the engine that is in ambient conditions above 4°C.

T-63 Operating Limits

Temperature limits for T63 installation

Measurement	Upper Limit °C	Lower Limit °C
Engine Stabilised TOT	749	350
Mixed Exhaust Gases	200	None
Engine Oil Out	107	0
PTO Oil Out	107	0
Dyno Water Out	60	1

Speed limits for T63 installation

Measurement	Upper Limit %	Lower Limit %
N_1	104	None
N_2 @ Idle	71	59
N_2 @ Normal Operation	102	98
N_2 @ Loss of Load	120	N/A

Pressure limits for T63 installation

Measurement	Upper Limit (Bar Gauge)	Lower Limit (Bar Gauge)
Engine Oil	8.96	6.21
PTO Oil	1	0.5
Engine Torque Sensor	6.89	2.07
Fuel Supply	0.7	0.4

(Note: PTO = Power Take-Off)

Torque limits for T63 installation

Measurement		Nm	Upper Limit (Bar Gauge)	kW
Torque	Continuous	337	5.86	212
	30 min limit	397	6.89	250
	10 sec limit	434	7.52	273

3. Normal Starting

CAUTION: Our engine incorporates a low energy exciter. Operating time limits are as follows: 2 minutes on, 3 Minutes off; 2 minutes on, 23 minutes off.

CAUTION: If the N2 turbine is not rotating by 25% N1 speed abort the Start. A second or third start attempt may be made; if the Condition still exists refer to Section III, Troubleshooting Table 6, Item 58 of Rolls Royce 250-C18 Series Operation and Maintenance Manual.

CAUTION: If for any reason the engine is shut down after fuel has been introduced to the combustion chamber but before ignition has occurred. The engine should be vented a number of times and a wait period of ten minutes must be observed before attempting restart. (This should be adhered to in order to ensure no excess fuel may be found within the engine).

The following procedure should be used for all engine starts in the gas turbine test cell:

- **l.** Rotate the N2 throttle lever to the position designated on the lever body.
- **m.** Check that the engine fuel supply pressure is reading ~0.5 bar.
- **n.** Ensure the residual TOT be no more than 150°C when light-off is attempted.
- **o.** On the desk mounted instrument panel: switch on the master, starter and spark switches.
- **p.** In ETA on controlling computer:
    1. Turn on “Start Logging” button in toolbar
    2. In the Auto Test tab, on the ETA-Automation Sequence Panel: Right click on “Step: 1 (*1)” and click “Start From Here…”
- **q. Watch and check to ensure the following occurs automatically:**

PRE- START:

1. In the Auto Test Tab of ETA:
    - i. The “Access” button on the “Dyno Control” panel should be depressed, and the “Access Status” LED should illuminate -both should turn green.
2. On the LCD of the X-act controller in the bottom left corner:
    - i. Control Mode should change to “α/n”
    - ii. Speed should be set to 3600 rpm and
    - iii. Throttle set point should be 0
3. Back in the Auto Test Tab of ETA:
    - i. The “Ignition” button on the “Dyno Control” panel should be depressed, and the “Ignition Status” indicator in “Dyno Status” panel should illuminate –both should turn green
4. In the Auto Test Tab of ETA on the “Supply Relays” panel the following buttons should turn green, indicating they have been enabled:
    - i. The “Fuel Supply” button (enables the emergency shut-off valve)
    - ii. The “Fuel Pump” button (enables the boost pump)
    - iii. The “Oil Pump” button
    - iv. The “PY Vent” button (closes the PY Vent)
5. In the Auto Test Tab of ETA on the “Power Relays” panel the following buttons should turn green, indicating they have been enabled:
    - i. The “Master Ignition” button
    - ii. The “Spark Signal” button
    - iii. The “Starter” button

STARTUP – GROUND IDLE:

6. At 12% N1 speed the throttle set point should be ramped to 40%.
7. Check Light-Off occurs
8. In the Auto Test Tab of ETA on the “Power Relays” panel the following
    - i. At 58% N1 speed the “Starter” and “Spark Signal” buttons should turn off –both should change red in colour
9. Start is complete when a stable N1 speed of 59 - 65 % is reached.
10. Check that the oil pressure is within limits, if not immediately shut- down.

GROUND IDLE – FLIGHT IDLE:

11. When Oil Temperature (“T Engine Oil Out”) reaches 50°C, dynamometer speed and throttle position should be ramped to 6000 rpm and 66% respectively.
12. At 100% N2 Speed, flight idle has been attained.
13. The engine will stabilise at flight idle conditions for 3 minutes. The automation procedure may be paused at this point and testing undertaken at these conditions. Alternatively after 3 minutes (if left to run) the automation sequence will shut down the engine.

15. TERMINATING A PROCEDURE

Engine Shut-down

It is recommended to read the engine operation section of the maintenance and operations manual to gain a full understanding of all aspects of the engine behaviour so as to be able to deal with problems that occur immediately and in the correct manner.

n. Continually monitor all systems to ensure the engine and all subsystems stay within limits.
o. Once testing is complete return the load to idle load.
p. If the ETA automation sequence was paused the play button will need to be clicked to resume automated operation, continuing with shut down.
q. Watch and check to ensure the following occurs automatically:

FLIGHT IDLE –GROUND IDLE:

1. Dynamometer speed and throttle position should be ramped down to 3600 rpm and 40% respectively.
2. At N1 & N2 = 60% speed the engine must stabilise for 2 minutes in ground idle.

SHUT DOWN:

1. Throttle position should be ramped down to 0%.
2. Monitor the TOT gauge for after fires. In the case of after fires execute step “6e”.

r. If TOT rises above 200°C motor (“vent”) the engine by turning on the “Start” switch till N1 speed reaches 10% (the “Spark” switch must be off during this procedure). Repeat if necessary.
s. Once TOT has dropped to ~150°C the “Master” switch may be turned off.
t. On the controlling computer in ETA turn off the following:
u. “Master Ignition”, “Starter” and “Spark” in the “Power Relays” panel.
v. Switch off the “PY Bleed”, “Oil Pump”, “Fuel Pump” and “Fuel Supply” buttons in the “Supply Relays” panel.
w. Click “Stop Logging’ button in toolbar.

16. EMERGENCY SHUT DOWN OF SYSTEM

There are two methods for emergency shutdown. Each of these methods functions independently from the other, thus any one of the two may be used at any point to achieve immediate results.

D. Emergency Engine Shutdown

Change “Set Throttle” to 0 and turn off the master switch on the desktop mounted instrument panel.
This will result in the shutoff of both fuel and power to the engine.

E. Emergency Fuel Shutoff Buttons

Two fuel shutoff buttons have been installed. The two large red buttons are located as follows:

c. In the control room near the desktop mounted instrument panel
d. On the wall above the fuel filtering system.

Each of these buttons functions independently and when pressed will cut off fuel to the engine via the solenoid valve located on the inner wall of the test cell.

F. Emergency Idle Mode

A third emergency method is also available in the form of a solenoid valve attached to the Py pneumatic signal line. Opening this solenoid valve bleeds the air from this line to the atmosphere resulting in the engine dropping into idle mode. The method to achieve this is as follows:

On the controlling computer in ETA:

b. Click the “Py Vent” button on the “Supply Relays” panel

17. CRITICAL EQUIPMENT LIST

Ensure a spill kit is available for fluid spills

Ensure fire extinguishers are located in the vicinity in the case of fire

18. GENERAL MAINTENANCE

Engine oil should be tested on a regular basis: Oil should be drawn from the system where it exits the engine and sent for analysis. Oil condition should be analysed and an engine wear test carried out on the oil. In the event that laboratory analysis indicates that the oil should be changed then oil in both the PTO and main engine oil tanks must be completely drained and renewed to ensure the engine stays in good working condition. When this oil purge is carried out three oil system checks should also be done. These checks are as follows:

- Remove and clean the oil filter located on the top of the engine (NOTE: a syringe should be used to draw out the oil in this cavity before removing the filter otherwise the dirt from the filter may wash out into the system)

Procedure number:	*Procedure revision date:*

SAFETY OPERATING PROCEDURE BLOCK STRUCTURE:

Job	Job Step	Method	Hazard	Risk	Control Measure	Task observation	
						Task executed effectively	**Deviations noticed**
Sub-System Activation - Electrical	1a	Check that all connections to the 24 V power supply (2 x 12 V batteries) in the test cell are secure	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		
	1b	Make sure there are no spilled fluids, especially in close proximity to any electrical wiring	Slipping Electric shock Exposure	Spilled fluids, Exposed/ broken wires Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	1c	Ensure that the connections to the starter motor are secured to the engine and the motor is itself secure.	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		
	1d	Check the connection to the ignition exciter is secured as well as the leads connecting to the magnetic chip detectors.	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		

	1e	Check the DB board to make sure that all appropriate switches are active.					
	1f	Open the PLC and in the top left corner switch on breakers 1, 2 and 4.					
	1g	Switch on the gas turbine controlling computer as well as the dynamometer controller.					
	1h	Entries on computer System					
Sub-System Activation - Oil	2a	Check the level of oil in both the primary oil tanks by removing the filler caps of each tank. The dip sticks should indicate that the tanks are sufficiently full.	Slipping Exposure	Spilled fluids, Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	2b	Check that all piping between the oil storage tanks and the engine are properly connected and that there are no disconnected pipes; be sure to check each thermocouple and pressure tapping connections.	Slipping Electric shock Exposure	Spilled fluids, Exposed/ broken wires Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	2c	Check that the bypass ball valve on the PTO					

		oil line is half way open, if not open to this position.					
	2d	Entries on controlling computer					
	2e	If the pressure is below 0.5 bar gauge further restrict the oil bypass route by closing the ball valve a small amount, if above 1 bar reduce the restriction as required					
Sub-System Activation - Water	3a	Ensure all pipes within the test cell are secured as desired and unused connections are shut.	Slipping Exposure Lacerations	Spilled fluids, Toxic substances Sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	3b	Check that the Continuous-Flow Combustion Rig has been isolated via the two shut-off valves, on the right side of its wall mounted control panel.					
	3c	Switch on the cooling tower fan on the DB board outside the Gas Turbine Control Room.					

	3d	Check that the fan is operational and there is sufficient water in the cooling tower. Open the fresh water supply valve to top up tank if not sufficiently full.					
	3e	Turn on Pumps and Valves A & B in pump room	Slipping	Spilled fluids	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	3f	Check that the pressure gauge within the test cell is registering and for any leaks that may have started.	Slipping	Spilled fluids	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	3g	Monitor the dyno outlet water temperature during operation to ensure the temperature remains below 40°C.					
Sub-System Activation - Ventilation	4a	Walk through the test cell and ensure there are no loose items that may be sucked into the ventilation system.					
	4b	Ensure that there are no blockages in front of the inlet (remove the	Finger Pinch	Door			

		gas turbine inlet cover if not already done) or exhaust and firmly secure the test cell doors.					
	4c	Switch on the orange DB board containing the supply and exhaust fan variable speed drives.					
	4d	Ensure both emergency stop switches are pulled out, located on the orange DB board outside the operating room and on the control box in the control room.					
	4e	Note the pressure inside the test cell from the ambient pressure transducer.					
	4f	Dial both the speed indicators to about 20% and start the fans one at a time.					
	4g	Slowly increase the speed of the fans one by one to attain full ventilation					
Sub-System Activation - Fuel	5a	All fittings and piping must be checked to ensure they are all appropriately connected and secure.	Slipping in spilled fluids, Exposure to toxic substances,	Slipping in spilled fluids, Exposure to toxic substances,	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat,		

			lacerations from sharp surfaces	lacerations from sharp surfaces	rubber gloves & safety eyewear. Keep a first aid kit handy.		
	5b	The supply and return fuel lines should be attached to the fuel drums to be used and the both of the shut-off valves should be set either to the left or right for the supply from either drum A or B.	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	5c	The shut-off valve between the fuel filter and the flow meter must be in the open position					
	5d	The 3-way valve between the engine and the emergency shut-off valve must be oriented to enable flow to the engine and not to the purge point. The line must be firmly secured to the fuel inlet on the engine.					
	5e	Entries on controlling computer					
Engine Light Off – Normal Start		Sequence of events carried out in control room to start up the gas turbine and achieve operation in idle mode.	Hearing Loss	Gas Turbine Noise	Wear ear plugs/muffs		

Engine Operation		Sequence of events carried out in control room to operate the gas turbine at varying speeds and loads.	Hearing Loss	Gas Turbine Noise	Wear ear plugs/muffs		

Deviations noticed:	**Corrective action:**

EQUIPMENT, METHODS AND PROCEDURES CAN NOT BE USED WITHOUT BEING DECLARED COMPETENT BY AN OBSERVER (QUALIFIED PERSON).

Procedure number:	Trainee:	Control Number:	Signature:	Observer:	Control Number:	Signature:	Date:

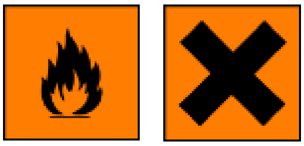
I HEREBY ACKNOWLEDGE RECEIPT OF THE ABOVE-MENTIONED DOCUMENT AND DECLARE THAT I HAVE READ AND UNDERSTAND THE CONTENTS AND THAT I WILL ADHERE TO THIS PROCEDURE/WORK INSTRUCTION DURING THE PERFORMANCE OF MY DUTIES.

3. LabVIEW Automatic Operating Procedure

University of Cape Town
Sasol Advanced Fuels Laboratory

OPERATING PROCEDURE:

BE AWARE OF RISKS PERTAINING TO TASK



Procedure number:	
Procedure Description:	**Operating procedure for T63 gas turbine using LabVIEW Automation**
Procedure compiled by:	Leanne Robertson
Procedure revision date:	15 July 2013
Procedure approved by:	
Nature of revision:	To include changes made in operating procedure ☒ To include instrument modifications ☒ Changes made to wording in procedure document ☐ Other:________________________________ ☐
Re-training required:	**Yes** ☐ **No** ☒ (**Comment:** Who exactly is this aimed at? Who requires re-training?)

NAME OF THE PROCEDURE

19. GENERAL

Objective

The standard operating procedure laid out in this document is provided to ensure safe operation of the T63-A-700 Gas Turbine.

Scope

The operating procedure described herein details the following:

- pre-start up inspections
- start-up procedures for each of the supporting sub-systems
- start-up procedure for the T63 gas turbine
- procedure for running the gas turbine at full speed under load
- shut down procedure to be followed for the gas turbine
- shut down procedures for each of the supporting sub-systems

Operating limits of the gas turbine are also specified.

References

- Rolls–Royce Technical Publication: 250–C18 series Operation and Maintenance
- General MSDS for Naphtha, Jet Fuel and Diesel.
- A Test-Cell Installation of a Gas Turbine Engine to Investigate the Performance Advantages of Low Aromatic Fuel; Appendix D- Operational Procedures; Nigel Bester; 2008

20. PRINCIPLE HAZARDS

- Flammable liquids
- Spilling of liquids
- Temperature extremes up to 700°C
- Petroleum products at elevated temperature (hot liquids)

21. PERSONAL PROTECTIVE EQUIPMENT

Closed shoes (safety shoes, or boots) should be worn at all times when in the laboratory and the following additional protective equipment should be worn according to the area in which you are working.

Control Room

Hearing protection during engine operation

Test Cell

Laboratory coat or overall jacket
Safety glasses
Safety gloves (Leather, rubber or latex, depending on application)
NOTE: The test cell may not be entered when the engine is running

Fuel Storage Room

Laboratory coat or overall jacket
Safety glasses

Safety gloves (Leather, rubber or latex, depending on application)

22. FIRST AID AND MEDICAL CARE RELATING TO MSDS: NAPHTHA, DIESEL AND KEROSENE.

Eye contact

Check for and remove any contact lenses. Immediately flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical attention immediately.

Skin contact

In case of contact, immediately flush skin with plenty of water for at least 15 minutes while removing contaminated clothing and shoes. Wash skin thoroughly with soap and water or use recognised skin cleanser. Wash clothing before reuse. Clean shoes thoroughly before reuse. Get medical attention immediately.

Inhalation

Move exposed person to fresh air. If not breathing, if breathing is irregular or if respiratory arrest occurs, provide artificial respiration or oxygen by trained personnel. Loosen tight clothing such as a collar, tie, belt or waistband. Get medical attention immediately.

Ingestion

Wash out mouth with water. Do not induce vomiting unless directed to do so by medical personnel. Never give anything by mouth to an unconscious person. Get medical attention immediately.

Protection of first-aiders

No action shall be taken involving any personal risk or without suitable training. It may be dangerous to the person providing aid to give mouth-to-mouth resuscitation.

Notes to physician

No specific treatment. Treat symptomatically. Contact poison treatment specialist immediately if large quantities have been ingested or inhaled.

Lacerations

Stay Safe. If you are not the victim, practise first aid measures and wear personal protective equipment, latex gloves, safety spectacles, long sleeves.

Control the bleeding before anything else. Putting pressure directly on the laceration while holding it above the level of the heart for 15 minutes should be enough to stop bleeding. Seek medical care; contact medical station immediately/dispatch ambulance.

23. GENERAL PROCEDURE

Apparatus

The Rolls Royce Allison T63-A-700 gas turbine is a turbo shaft engine installed at the Sasol Advanced Fuels Laboratory for use in fuels testing.

Preparation and preventative actions (Pre-start up checks)

Prior to activating any engine sub-systems the following checks must be completed:

- **o.** Check the engine Log Book to ensure all maintenance work is complete and the engine is operational.
- **p.** If maintenance has been performed check that the specific component has been reinstalled and all associated connections made/bolts fastened.
- **q.** Check the floor of the test cell for any loose items that could be ingested by the engine and remove them.
- **r.** Look at the compressor inlet to ensure no foreign objects are present to be ingested. Check the shaft guard and free-wheeling unit for small items of debris.
- **s.** Check all electrical and mechanical sensing lines are secured and unable to be disconnected, burned or ingested by the engine.
- **t.** Ensure all mechanical and electrical connections to the boom box are secure.

- **u.** Ensure the air supply path to the test cell is free of obstructions.

Sub-System Activation

Once the pre-start up checks are complete the various engine subsystems must be activated in the following order, stepping through the individual 'Normal Operation' procedures listed below:

- **11.** Electrical
- **12.** Oil
- **13.** Water
- **14.** Ventilation
- **15.** Fuel

5. **Electrical (Normal Operation)**
   - **r.** Check that all connections to the 24 V power supply (2 x 12 V batteries) in the test cell are secure and that the batteries have sufficient charge by looking at the indicators on their upper surface (indicators should be green if sufficiently charged).
   - **s.** Make sure there are no spilled fluids, especially in close proximity to any electrical wiring.
   - **t.** Ensure that the connections to the starter motor are secured to the engine and the motor is itself secure.
   - **u.** Check the connection to the low tension capacitor discharge ignition exciter is secured as well as the leads connecting to the magnetic chip detectors.
   - **v.** Check the distribution board (DB board) to make sure that all appropriate switches are active.
   - **w.** Open the Programmable Logic Controller (PLC) and in the top left corner switch on breakers 1, 2 and 4.
   - **x.** Switch on the gas turbine controlling computers as well as the dynamometer controller.
   - **y.** Ensure the cable connecting the PCI CAN cards of the X-act controller and LabVIEW host machine is in place.
   - **z.** Computer Systems:

   On host computer on which ETA is run:
   - Open ETA software.
   - Put ETA into “online” mode (green robot icon)
   - In the “Dyno Comms” panel:
     1. Click “Access” button
     2. Check “Access Status” indicator in “Dyno Status” panel turns green
     3. Click “Ignition” button
     4. Check “Ignition Status” indicator in “Dyno Status” panel turns green

   On the host computer on which LabVIEW is run:
   - Start up the FTP Server by running the program “smallftp.exe”.
   - In LabVIEW:
     1. First deploy the shared variables for both the real time VI and Host VI then click the arrow that deploys first the real time VI then the Host VI.
     2. Ensure fuel control mode is selected as “MANUAL”

6. **Oil (Normal Operation)**
   - **l.** Check the level of oil in both the primary oil tanks by removing the filler caps of each tank. The dip sticks should indicate that the tanks are sufficiently full.
   - **m.** Check that all piping between the oil storage tanks and the engine are properly connected and that there are no disconnected pipes; be sure to check each thermocouple and pressure tapping connections.

- **n.** Check that the bypass ball valve on the PTO oil line is half way open, if not open to this position.
- **o.** On the controlling computer:
    5. Switch on the PTO oil pump in the “Supply Relays” panel of ETA.
    6. Wait a moment and ensure that the oil is flowing as intended and make sure the pressure transducer is registering a positive pressure on the controlling computer (~0.5 - 1 bar-gauge).
- **p.** If the pressure is below 0.5 bar gauge further restrict the oil bypass route by closing the ball valve a small amount, if above 1 bar reduce the restriction as required.

5. **Water (Normal Operation)**
    - **o.** Ensure all pipes within the test cell are secured as desired and unused connections are shut.
    - **p.** Check that the Continuous-Flow Combustion Rig has been isolated via the two shut-off valves, on the right side of its wall mounted control panel.
    - **q.** Switch on the cooling tower fan on the DB board outside the Gas Turbine Control Room. (Optional step dependent on ambient conditions and temperature)
    - **r.** Check that the fan is operational and there is sufficient water in the cooling tower. Open the fresh water supply valve to top up tank if not sufficiently full.
    - **s.** In the pump room:
        1. Fully open shut-off valve A and switch on the cooling tower supply pump (Pump A).
        2. Check that the water tank has fully drained if full.
        3. Fully open shut-off valve B and switch on the test cell supply pump (Pump B).
    - **t.** Check that the pressure gauge within the test cell is registering and for any leaks that may have started.
    - **u.** Monitor the dyno outlet water temperature during operation to ensure the temperature remains below 40°C.

8. **Ventilation (Normal Operation)**
    - **o.** Walk through the test cell and ensure there are no loose items that may be sucked into the ventilation system.
    - **p.** Ensure that there are no blockages in front of the inlet (remove the gas turbine inlet cover if not already done) or exhaust and firmly secure the test cell doors.
    - **q.** Switch on the orange DB board containing the supply and exhaust fan variable speed drives.
    - **r.** Ensure both emergency stop switches are pulled out, located on the orange DB board outside the operating room and on the control box in the control room.
    - **s.** Note the pressure inside the test cell from the ambient pressure transducer.
    - **t.** Dial both the speed indicators to about 20% and start the fans one at a time.
    - **u.** Slowly increase the speed of the fans one by one to attain full ventilation (Full ventilation is reached when one of the fans reaches 100% and the test cell pressure is as it was before the fans were activated).

9. **Fuel (Normal Operation)**
    - **k.** All fittings and piping must be checked to ensure they are all appropriately connected and secure.
    - **l.** The supply and return fuel lines should be attached to the fuel drums to be used and the both of the shut-off valves should be set either to the left or right for the supply from either drum A or B.
    - **m.** The shut-off valve between the fuel filter and the flow meter must be in the open position allowing fuel flow to the test cell and the 3-way valve between the air

separation unit and the back pressure regulator must be pointing in the direction of the regulator (i.e. not open to atmosphere).

n. The 3-way valve between the engine and the emergency shut-off valve must be oriented to enable flow to the engine and not to the purge point. The line must be firmly secured to the fuel inlet on the engine.

o. On the controlling computer:
  1. Ensure that there is sufficient fuel in the drum by referring to the fuel level indicator in ETA. (The fuel level indicator in the fuel drum often sticks – ensure it is free before commencing operation)
  2. Enable the boost pump by clicking the “Fuel Pump” button on the “Supply Relays” panel in ETA.
  3. Click the “Fuel Supply” button on the “Supply Relays” panel in ETA to enable the emergency shut-off valve.

Engine Light-off

It is recommended to read the entire light-off procedure in the maintenance and operations manual to gain a full understanding of all aspects of the engine behaviour. Light-off is a rapid process and the operator must already possess all necessary knowledge.

All the above 'Normal Operation' procedure lists for the various subsystems should have been complete at this stage. The following is the procedure for normal starting of the engine that is in ambient conditions above 4°C.

T-63 Operating Limits

Temperature limits for T63 installation

Measurement	Upper Limit °C	Lower Limit °C
Engine Stabilised TOT	749	350
Mixed Exhaust Gases	200	None
Engine Oil Out	107	0
PTO Oil Out	107	0
Dyno Water Out	60	1

Speed limits for T63 installation

Measurement	Upper Limit %	Lower Limit %
N_1	104	None
N_2 @ Idle	71	59
N_2 @ Normal Operation	102	98
N_2 @ Loss of Load	120	N/A

Pressure limits for T63 installation

Measurement	Upper Limit (Bar Gauge)	Lower Limit (Bar Gauge)
Engine Oil	8.96	6.21
PTO Oil	1	0.5
Engine Torque Sensor	6.89	2.07
Fuel Supply	0.7	0.4

(Note: PTO = Power Take-Off)

Torque limits for T63 installation

Measurement		Nm	Upper Limit (Bar Gauge)	kW
Torque	Continuous	337	5.86	212
	30 min limit	397	6.89	250

	10 sec limit	434	7.52	273

4. Normal Starting

CAUTION: Our engine incorporates a low energy exciter. Operating time limits are as follows: 2 minutes on, 3 Minutes off; 2 minutes on, 23 minutes off.

CAUTION: If the N2 turbine is not rotating by 25% N1 speed abort the Start. A second or third start attempt may be made; if the Condition still exists refer to Section III, Troubleshooting Table 6, Item 58 of Rolls Royce 250-C18 Series Operation and Maintenance Manual.

CAUTION: If for any reason the engine is shut down after fuel has been introduced to the combustion chamber but before ignition has occurred. The engine should be vented a number of times and a wait period of ten minutes must be observed before attempting restart. (This should be adhered to in order to ensure no excess fuel may be found within the engine).

The following procedure should be used for all engine starts in the gas turbine test cell:

r. Rotate the N2 throttle lever to the position designated on the lever body.
s. Check that the engine fuel supply pressure is reading ~0.5 bar.
t. Ensure the residual TOT be no more than 150°C when light-off is attempted.
u. In ETA:
  1. Turn on “Start Logging” button in toolbar
  2. Switch on the “PY Bleed” button in the “Supply Relays” panel.
  3. Switch on the “Master Ignition” button on the “Power Relays’ panel

v. On the desk mounted instrument panel: switch on the master, starter and spark switches.
w. In LabVIEW:
  1. Turn on “Trigger Acquisition” button
  2. Turn on “Start Engine” button in Engine Tab

x. Watch and check to ensure the following occurs automatically:

PRE- START:

1. In the Dynamometer Tab of LabVIEW:
    - i. The “Access” button on the “Control” panel should be depressed, and the access status LED should illuminate.
    - ii. The control mode toggle switch should be up and the “Speed Control Mode” indicator should be illuminated.
    - iii. The “Ignition” button on the “Control” panel should be depressed, and the Ignition Status indicator should illuminate
2. In the Engine Tab of LabVIEW:
    - i. The “Open Overspeed Valve” button should be depressed
    - ii. The “Master”, “Spark” and “Starter” toggle switches should all come on.
3. On the LCD of the X-act controller in the bottom left corner:
    - i. Control Mode should be “α/n”
    - ii. Speed should be set to 3600 rpm and
    - iii. Throttle set point should be 0

STARTUP – GROUND IDLE:

4. At 12% N1 speed the throttle set point should be ramped to 45%.
5. Check Light-Off occurs
6. In the Engine Tab of LabVIEW
    - i. At 58% N1 speed the “Starter” and “Spark” switches should toggle to off
7. Start is complete when a stable N1 speed of 59 - 65 % is reached.
8. Check that the oil pressure is within limits, if not immediately shut- down.

GROUND IDLE – FLIGHT IDLE:

9. When Oil Temperature (“Oil Temp”) reaches 50°C, dynamometer speed and throttle position should be ramped to 6000 rpm and 75% respectively.
10. At 100% N2 Speed, flight idle has been attained.
11. The “Engine Ready” indicator will be illuminated. The start-up automation procedure has been concluded at this point and testing may be undertaken at these conditions.

24. TERMINATING A PROCEDURE

Engine Shut-down

It is recommended to read the engine operation section of the maintenance and operations manual to gain a full understanding of all aspects of the engine behaviour so as to be able to deal with problems that occur immediately and in the correct manner.

x. Continually monitor all systems to ensure the engine and all subsystems stay within limits.
y. Once testing is complete return the load to idle load.
z. In LabVIEW:
  1. Turn on “Shutdown Engine” button in Engine Tab

aa. Watch and check to ensure the following occurs automatically:

FLIGHT IDLE –GROUND IDLE:

  1. Dynamometer speed and throttle position should be ramped down to 3600 rpm and 40% respectively.
  2. At N1 & N2 = 60% speed the engine must stabilise for 2 minutes in ground idle.

SHUT DOWN:

  3. Throttle position should be ramped down to 0%.

VENT:

  3. If TOT rises above 200°C the “Start” switch will be turned on till N1 speed reaches 10% then turned off (the “Spark” switch must be off during this procedure). This vents air through the engine and will be repeated three times.
  4. Once TOT has dropped to ~150°C the “Master” switch will be turned off
  5. Click “End Acquisition’ button
  6. In ETA turn off the following:
    i. “PY Bleed” button in the “Supply Relays” panel.
    ii. “Oil Pump” button in the “Supply Relays” panel.
    iii. “Fuel Pump” button in the “Supply Relays” panel.
    iv. “Fuel Supply” button in the “Supply Relays” panel.
    v. “Master Ignition” button on the “Power Relays’ panel
    vi. Click “Stop Logging’ button in toolbar.

25. EMERGENCY SHUT DOWN OF SYSTEM

There are two methods for emergency shutdown. Each of these methods functions independently from the other, thus any one of the two may be used at any point to achieve immediate results.

G. Emergency Engine Shutdown

Rotate the N1 lever to the minimum position and turn off the master switch on the desktop mounted instrument panel.
This will result in the shutoff of both fuel and power to the engine.

H. Emergency Fuel Shutoff Buttons

Two fuel shutoff buttons have been installed. The two large red buttons are located as follows:

  e. In the control room near the desktop mounted instrument panel

f. On the wall above the fuel filtering system.

Each of these buttons functions independently and when pressed will cut off fuel to the engine via the solenoid valve located on the inner wall of the test cell.

I. Emergency Idle Mode

A third emergency method is also available in the form of a solenoid valve attached to the Py pneumatic signal line. Opening this solenoid valve bleeds the air from this line to the atmosphere resulting in the engine dropping into idle mode. The method to achieve this is as follows:

On the controlling computer in ETA:

c. Click the “Py Vent” button on the “Supply Relays” panel

26. CRITICAL EQUIPMENT LIST

Ensure a spill kit is available for fluid spills
Ensure fire extinguishers are located in the vicinity in the case of fire

27. GENERAL MAINTENANCE

Engine oil should be tested on a regular basis: Oil should be drawn from the system where it exits the engine and sent for analysis. Oil condition should be analysed and an engine wear test carried out on the oil. In the event that laboratory analysis indicates that the oil should be changed then oil in both the PTO and main engine oil tanks must be completely drained and renewed to ensure the engine stays in good working condition. When this oil purge is carried out three oil system checks should also be done. These checks are as follows:

- Remove and clean the oil filter located on the top of the engine (NOTE: a syringe should be used to draw out the oil in this cavity before removing the filter otherwise the dirt from the filter may wash out into the system)

Procedure number:	*Procedure revision date:*

SAFETY OPERATING PROCEDURE BLOCK STRUCTURE:

Job	Job Step	Method	Hazard	Risk	Control Measure	Task observation	
						Task executed effectively	**Deviations noticed**
Sub-System Activation - Electrical	1a	Check that all connections to the 24 V power supply (2 x 12 V batteries) in the test cell are secure	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		
	1b	Make sure there are no spilled fluids, especially in close proximity to any electrical wiring	Slipping Electric shock Exposure	Spilled fluids, Exposed/ broken wires Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	1c	Ensure that the connections to the starter motor are secured to the engine and the motor is itself secure.	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		
	1d	Check the connection to the ignition exciter is secured as well as the leads connecting to the magnetic chip detectors.	Electric Shock	Exposed/ broken wires	Wear rubber soled shoes		

	1e	Check the DB board to make sure that all appropriate switches are active.					
	1f	Open the PLC and in the top left corner switch on breakers 1, 2 and 4.					
	1g	Switch on the gas turbine controlling computer as well as the dynamometer controller.					
	1h	Entries on computer System					
Sub-System Activation - Oil	2a	Check the level of oil in both the primary oil tanks by removing the filler caps of each tank. The dip sticks should indicate that the tanks are sufficiently full.	Slipping Exposure	Spilled fluids, Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	2b	Check that all piping between the oil storage tanks and the engine are properly connected and that there are no disconnected pipes; be sure to check each thermocouple and pressure tapping connections.	Slipping Electric shock Exposure	Spilled fluids, Exposed/ broken wires Toxic substances	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	2c	Check that the bypass ball valve on the PTO					

		oil line is half way open, if not open to this position.					
	2d	Entries on controlling computer					
	2e	If the pressure is below 0.5 bar gauge further restrict the oil bypass route by closing the ball valve a small amount, if above 1 bar reduce the restriction as required					
Sub-System Activation - Water	3a	Ensure all pipes within the test cell are secured as desired and unused connections are shut.	Slipping Exposure Lacerations	Spilled fluids, Toxic substances Sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	3b	Check that the Continuous-Flow Combustion Rig has been isolated via the two shut-off valves, on the right side of its wall mounted control panel.					
	3c	Switch on the cooling tower fan on the DB board outside the Gas Turbine Control Room.					

	3d	Check that the fan is operational and there is sufficient water in the cooling tower. Open the fresh water supply valve to top up tank if not sufficiently full.					
	3e	Turn on Pumps and Valves A & B in pump room	Slipping	Spilled fluids	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	3f	Check that the pressure gauge within the test cell is registering and for any leaks that may have started.	Slipping	Spilled fluids	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear.		
	3g	Monitor the dyno outlet water temperature during operation to ensure the temperature remains below 40°C.					
Sub-System Activation - Ventilation	4a	Walk through the test cell and ensure there are no loose items that may be sucked into the ventilation system.					
	4b	Ensure that there are no blockages in front of the inlet (remove the	Finger Pinch	Door			

		gas turbine inlet cover if not already done) or exhaust and firmly secure the test cell doors.					
	4c	Switch on the orange DB board containing the supply and exhaust fan variable speed drives.					
	4d	Ensure both emergency stop switches are pulled out, located on the orange DB board outside the operating room and on the control box in the control room.					
	4e	Note the pressure inside the test cell from the ambient pressure transducer.					
	4f	Dial both the speed indicators to about 20% and start the fans one at a time.					
	4g	Slowly increase the speed of the fans one by one to attain full ventilation					
Sub-System Activation - Fuel	5a	All fittings and piping must be checked to ensure they are all appropriately connected and secure.	Slipping in spilled fluids, Exposure to toxic substances,	Slipping in spilled fluids, Exposure to toxic substances,	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat,		

			lacerations from sharp surfaces	lacerations from sharp surfaces	rubber gloves & safety eyewear. Keep a first aid kit handy.		
	5b	The supply and return fuel lines should be attached to the fuel drums to be used and the both of the shut-off valves should be set either to the left or right for the supply from either drum A or B.	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Slipping in spilled fluids, Exposure to toxic substances, lacerations from sharp surfaces	Wear rubber soled shoes, Keep spill kit in the near vicinity. Wear laboratory coat, rubber gloves & safety eyewear. Keep a first aid kit handy.		
	5c	The shut-off valve between the fuel filter and the flow meter must be in the open position					
	5d	The 3-way valve between the engine and the emergency shut-off valve must be oriented to enable flow to the engine and not to the purge point. The line must be firmly secured to the fuel inlet on the engine.					
	5e	Entries on controlling computer					
Engine Light Off – Normal Start		Sequence of events carried out in control room to start up the gas turbine and achieve operation in idle mode.	Hearing Loss	Gas Turbine Noise	Wear ear plugs/muffs		

Engine Operation		Sequence of events carried out in control room to operate the gas turbine at varying speeds and loads.	Hearing Loss	Gas Turbine Noise	Wear ear plugs/muffs		

Deviations noticed:	**Corrective action:**

EQUIPMENT, METHODS AND PROCEDURES CAN NOT BE USED WITHOUT BEING DECLARED COMPETENT BY AN OBSERVER (QUALIFIED PERSON).

Procedure number:	Trainee:	Control Number:	Signature:	Observer:	Control Number:	Signature:	Date:

I HEREBY ACKNOWLEDGE RECEIPT OF THE ABOVE-MENTIONED DOCUMENT AND DECLARE THAT I HAVE READ AND UNDERSTAND THE CONTENTS AND THAT I WILL ADHERE TO THIS PROCEDURE/WORK INSTRUCTION DURING THE PERFORMANCE OF MY DUTIES.