Internship report

Rolls-Royce plc

Image owned by Rolls-Royce plc [1]

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Internship duration: 2nd Sept 2013 till 7th March 2014

1 Summary

This report describes my experiences working as an intern with the Rolls-Royce lean burn combustion team. My six month placement has been very educational and challenging and it has allowed me to experience what it is like to work for a big, internationally operating company. The most important thing I have learned is that the activities of a combustion engineer are very diverse and challenging. Very often the big tasks at hand are complicated and require a lot of work and input from a large team of people. The work requires a firm understanding of the laws of physics to understand the fundamental principles of the technological challenges. At other times the number of variables in play becomes so large that it is easy to lose track of things and in that case it is even more important to stay focussed on the job in hand. The great variety of work has made the internship very enjoyable for me.

2 Acknowledgements

Apart from the work being interesting my colleagues made going to the office every morning so much more enjoyable. I would like to say thank you to my colleagues Andrea, Carl, Carrie, Hua Wei, Juan Carlos, Luca, Mike, Zakia, with whom I worked on a daily basis. They were always willing to help me out and I really enjoyed working with every one of them. Thank you goes out to Allan, Darren and Nick for supporting me on my experimental work.

I would like to especially thank Jochen for everything that he has taught me in the past couple of months and for all those times that he stayed in the office a just that little bit longer to help me out with something.

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3 Nomenclature

ACARE: Advisory Council for Aeronautics Research in Europe

AFR: Air-to-Fuel ratio

DAQ: Dynamic Data Acquisition (system)

FAR: Fuel-to-Air ratio

ICAO: International Civil Aviation Organisation

LTO: Landing and Take Off (cycle)

$NO_{x:}$ Nitrogen oxides (NO and NO_2)

SARS: Sub Atmospheric Relight rig

TRL: Technology Readiness Level

UHC: Unburnt Hydro Carbons

VCAS: Calibrated airspeed

4 Introduction

Rolls Royce plc is a designer and manufacturer of heavy-duty gas turbines for a variety of applications. Their products are used globally for military and civil aerospace applications, marine propulsion systems and energy production. My internship took place in the combustion subsystem of the civil large engines business. This department is responsible for the development and design of the combustion system for the current and future jet engines on large civil airplanes. In Figure 1 the Rolls-Royce Trent 1000 jet engine currently used to power the Boeing 787 Dreamliner is shown.

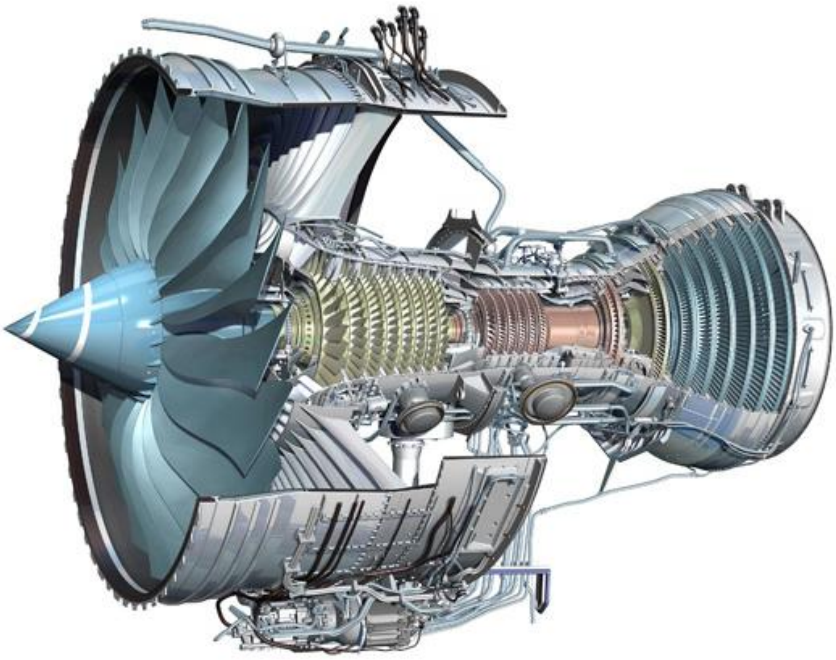

Figure 1 - Rolls-Royce Trent 1000 jet engine (Rolls Royce plc – 2014)

The design of a jet engine is a very complex and challenging process. In general the principle of a jet engine is described by the Brayton cycle. First air is compressed by a fan and multiple compressor stages. Then fuel is added and combusted in the combustion chamber. The final step is the extraction of work using a series of turbine stages. Part of this work is used to run the upstream fan and compressor stages and the remainder of this energy can be used for example to generate thrust as it is done for a jet engine.

4.1 Technology readiness level

The design process involves a large team of people from different departments and with different skills working together. To judge the maturity level of a technology Technology Readiness Levels (TRL), as defined by NASA (reference [3]), are used. This is a scale, ranging from 1 to 9. It rates the readiness of a technology to becoming a fully functional “flight proven” product or application. When a new concept or principle is invented or observed it is said to be at TRL 1 and it progresses up the scale as the technology is developed from fundamental scientific research up to a “flight proven” technological application. The combustion subsystem works on technologies ranging from TRL 1 to TRL 9.

In my work I was exposed to technology development up to TRL 6. At that level the functionality is demonstrated in a representative environment, as for example a research demonstrator engine.

4.2 Aero-Engine Combustion Systems

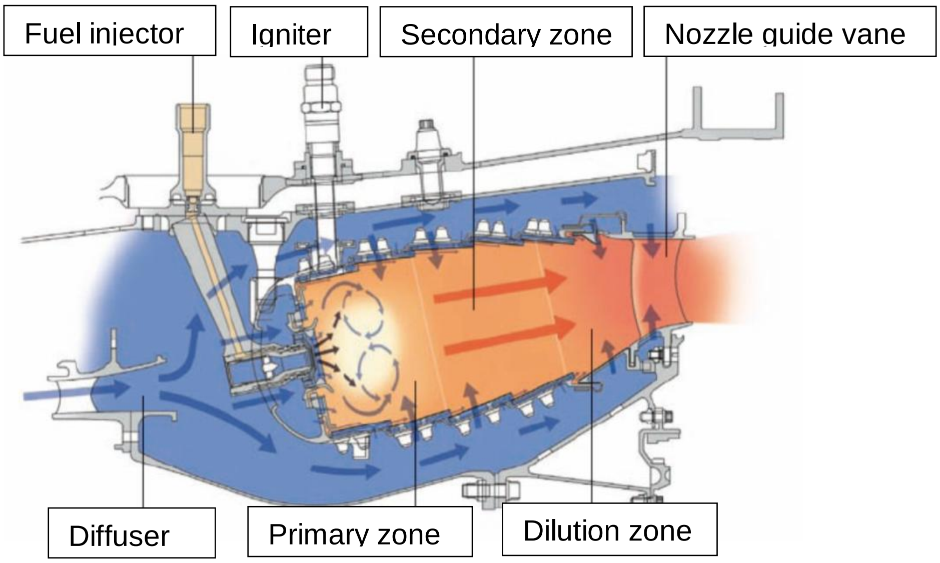

Figure 2 – Typical Rich burn combustor, (Rolls-Royce plc - 2014)

Most jet engines currently flying use a Rich Quench Lean (RQL) combustion system (Figure 2). Air from the high pressure compressor stage enters the annulus through the diffuser. The diffuser reduces the axial velocity and conditions the velocity field for entry into the combustor. Typically around 10-20% of airflow from the diffuser enters the combustor through the fuel spray nozzle. The majority of the remaining air is fed to the combustor through secondary ports in the combustor walls. Furthermore, some air is used for wall cooling of the combustor and some air is used for turbine cooling.

Inside the combustor three different zones can be distinguished, the primary zone, the secondary zone and the dilution zone. The primary zone is the area just downstream of the fuel injector. Low velocity recirculation zones are established for flame stabilisation reasons across the operating envelope of the engine. The fuel injected by the fuel spray nozzle is atomized, vaporized, mixed with air and burnt in the primary zone. The flame in this zone is very rich, typically an AFR of approximately 6, to allow for stable operating throughout the entire operating cycle. Due to the rich air to fuel ratios in the primary zone combustion products such as soot, CO and UHC are formed. These products can be consumed by mixing fresh air into the combustion process using the primary and secondary ports. This is an important step in controlling jet engine emissions and in achieving high combustion efficiencies. If the air is mixed in too slowly large amount of NOx are formed at peak temperature near stoichiometric air to fuel ratios. Hence the air is rapidly mixed into the combustor for RQL systems to avoid excessive NOx formation. However care has to be taken to keep the combustion temperature sufficiently high for consumption of CO and soot. At the end of the secondary zone the combustion process should be completed to avoid overheating of downstream engine parts. In the dilution zone even more air is introduced through the walls to shape the exit temperature profile to the requirements of the downstream engine components.

4.3 Environmental impact

Two unwanted by-products of the gas turbine are noise and emissions. The noise from a jet engine running at high power condition is substantial and is a disturbance in the vicinity of airports. The International Civil Aviation Organisation (ICAO) regulates the noise limits currently in effect. Aircraft noise has a variety of sources, the combustor is one of them but the contribution of a thermo acoustically stable combustor is not significant in comparison to the other sources of aircraft noise.

4.3.1 Jet engine emissions

The other by-products of jet engines are the emissions and are a direct result of the combustion process. The pollutants produced by jet engines are CO, CO_2, Unburnt Hydro Carbons (UHC), NO_x, $SO_{x,}$ smoke.

A jet engine will only produce small amounts of SO_x because the limits imposed on sulphur content of aviation fuel are sufficient to keep the production of SO_x below the required thresholds.

CO_2 and H_2O production are unavoidable for any combustion process using fossil fuels. The only way to reduce the amount of CO_2 and water vapour is to reduce the amount of fuel that is required, this means increasing the overall fuel efficiency of the system. CO_2 is a greenhouse gas and water vapour is an important contributor to contrail formation of the engine. The contrails contribute to the formation of cirrus cloud formations.

The production of CO, UHC and particulate matter are inversely related to the efficiency of the combustion process. CO and UHC are products of incomplete combustion and are mainly an issue for low power operating conditions like idling on the airport. The combustion efficiency is around 98% when idling and approximately 99.9% and above at cruise. CO is a poisonous gas and UHC is a contributing factor in the formation of smog and acid rain. Unburnt hydro carbons have a very distinctive odour that is a nuisance around airports.

The production of NO_x is strongly dependent on the flame temperature. NO_x formation begins when the flame temperature reaches roughly 1500K and for every 50K flame temperature increase the NO_x production is approximately doubled. The current method of quenching a rich flame produces considerable amounts of NO_x as the air introduced in the quenching zone will lead to the generation of a stoichiometric mixture at some point during the quenching process. The flame temperature is very high close to stoichiometry and hence a lot of NO_x is produced. One way to avoid NOx production is to avoid the flame having to go through stoichiometry or if that is not possible decrease the time spent at stoichiometric equivalence ratios. NO_x is mainly produced at medium to high power conditions because of the increased pressure and temperature in the combustion chamber. NO_x contributes to the formation of acid rain and the emission of NO_x at altitude causes ozone (O_3) production which in turn contributes to global warming.

Smoke and particulate matter production is dependent on the AFR, pressure and temperature in the combustor. Smoke is mainly produced at medium to high power conditions. All modern combustion systems are designed to avoid producing any visual smoke.

4.3.2 Global emission reduction strategy

Besides noise regulations the ICAO has also imposed regulations on the emissions of airplanes. The current regulations limit the emissions based on the standard Landing and Take Off cycle (LTO). They are referred to as CAEP/6. Its successor is more stringent and is called CAEP/8. These emissions standards currently limit the amount of NO_x in g of NO_x per kN of thrust against the overall pressure ratio of the engine.

The Advisory Council for Aeronautics Research in Europe (ACARE) has set a number of goals that the European aviation industry should strive to achieve in 2020 and 2050 to help maintain Europe's leading position in the field of aviation. The ACARE goal for 2050 requires an overall CO_2 reduction of 75%, an overall NO_x reduction of 90% and an overall noise reduction of 65%. In Figure 3 several Rolls-Royce engines and their performance in relation to the ACARE target for 2050 are shown.

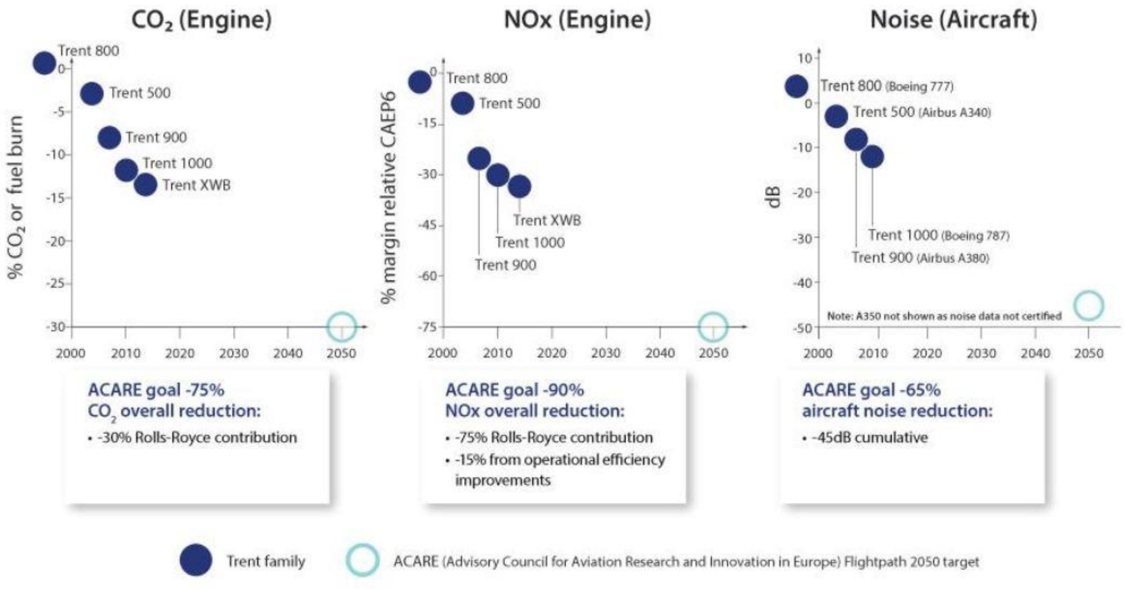

Figure 3 – Roll-Royce engines relative to ACARE 2050 targets (Rolls-Royce plc - 2014) [2]

4.3.3 Lean burn combustion system

Both CAEP/8 and ACARE 2020 require that NO_x emissions are reduced and the only way to achieve these reductions is switching from a rich burn combustion system to a lean burn combustion system. On a lean burn system most of the air enters the combustor through the main fuel spray nozzle (~70%). The remaining air is used for wall cooling purposes and turbine cooling requirements. Lean burn systems have been in use in industrial applications for some time and there are various ways to create a lean burn combustion system. The current method employed by several manufacturers is a staged combustion system that uses a rich pilot to create stability at low power conditions and a lean mains injector to achieve lower NO_x production at medium to high power operation.

4.4 Operational requirements

The combustor on a jet engine has to meet a variety of requirements. The airframe manufacturer specifies some of the engine operating conditions with the operational envelope for the aircraft. Other combustor requirements are set by emission and efficiency targets or by engine parts that interact with the combustor. The combustor must be able to relight both on the ground and at high altitude for obvious safety reasons. The combustion efficiency at idle must be sufficiently high (>98%) to prevent visible smoke formation and minimize CO and UHC production. The combustion efficiency at maximum power and cruise must be very high, larger than 99.9%, to minimize fuel consumption. The biggest expense in operating a jet engine is the fuel cost. A small decrease in combustion efficiency can have a large impact on the annual fuel costs.

During my internship I was involved in combustor testing for altitude relight and ground ignition and I was involved in emission experiments. The combustor arrangement can suffer a flameout for a variety of reasons. A flameout does not occur often however the combustor must be able to relight if this occurs within flight envelope of the aircraft. The combustor flameout limits can be improved with an increase in combustor volume and with a richer flame. The drawback is that NO_x production is higher with increased combustor volume and flame richness. The difficulty lies in finding a lean burn combustion system that hits the emission targets, shows sufficient relight capability and is thermo acoustically stable. There is always a trade-off between decreasing emissions and increasing the flameout boundaries.

The emission experiments are used to determine the combustor performance for a variety in operating conditions. The emissions experiments are carried out on a full annular rig. The combustor arrangement on this rig shows a similar performance to that of a jet engine but the setup lacks compressor and turbine stages as those found on an engine. This makes it possible to investigate the behaviour of various engine cycles within the same experiment. On an emissions build the composition of the exhaust gasses is analyzed, also temperature and pressure variations at a number of locations are recorded. The results are analyzed to determine if the combustion chamber meets the emissions and efficiency requirements and the exit profiles with either gas concentration or temperature are investigated for hotspots and other unexpected behaviour.

4.4.1 Thermo acoustic instabilities

From the applications in industry it is well known that lean burn combustion systems are susceptible to thermo acoustic instabilities. Thermo acoustic instabilities cause large pressure fluctuations in the combustion system that can lead to reductions in the life of the combustion system components.

The thermo acoustic instabilities occur when the heat release is coupled with one of the acoustic Eigen modes of the system. The coupling causes an increase in the pressure fluctuations of the system which limit component life.

It is challenging to predict the thermo acoustic behaviour of any gas turbine combustion system, on a jet engine especially so because of the variety of operating conditions. The experiments that are carried out usually have several dynamic pressure transducers fitted to make detection of thermo acoustic instabilities possible. These experiments are used to validate that the combustion system design is stable and the measured pressure amplitudes are sufficiently low. If sufficiently low amplitudes cannot be achieved passive damping techniques such as Helmholtz resonators could be used to reduce the onset of thermo-acoustic instabilities by absorbing the acoustic energy within the combustor. However these devices are tuned with narrow bandwidth over which sufficient acoustic absorption can be achieved. This can make it challenging to design a set of resonators which cover instability frequencies across the engine operating envelope.

4.5 Temperature profile transformations

The combustor arrangement on a gas turbine provides the turbines with hot air. The flow field, temperature profile and gas composition at the combustor exit contain important information required for the design of both the combustor and the downstream turbine stages. An estimation of these profiles at the combustor exit is obtained from experiments or from CFD modelling.

The temperature profile is specific to a certain fuel split, operating condition and geometry. The experiments required to obtain an accurate temperature profile are costly and the CFD modelling takes considerable amounts of time. To minimize the number of experiments and CFD models an existing temperature profile can be transformed to a different geometry or a different operating condition with the right assumptions. In Figure 4 an example temperature profile is shown, on the left the original is shown and on the right the transformed profile is shown. The temperature profile was created with the matlab routine “peaks” and the transformation is a gradient superimposed on the original temperature distribution hence the data has no physical meaning, but for the moment assume that it does. The maximum temperature in the figure on the right has increased the normalized dimensionless temperature by about 0.1[-]. The maximum temperature in the transformed temperature profile is larger than the allowed turbine entry temperature. Hence the failure mode associated with this fictional case would be a cause of concern.

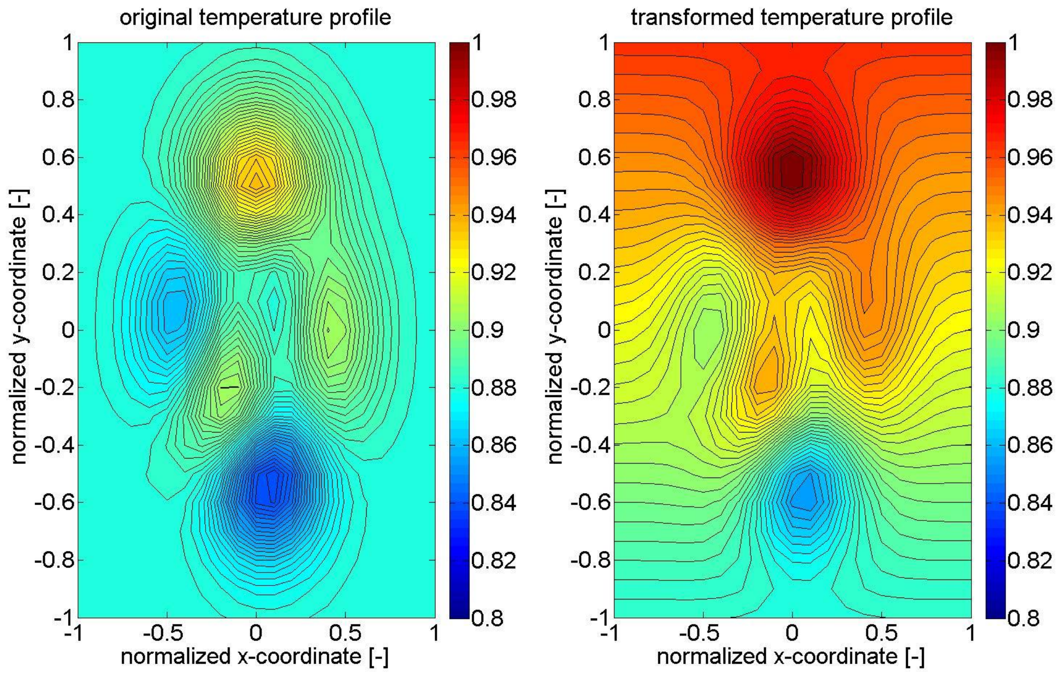

Figure 4 - Example temperature profile original and transformed

These transformations are a powerful analysis tool. I have used similar transformations to estimate adiabatic flame temperatures at various high power operating conditions for various fuel ratios and I have combined experimental results and CFD predictions into a single result for prediction purposes. They are also a useful tool for investigating failure modes as the above example has shown.

5 Experimental: Acoustic validation rig

5.1 Introduction

There are a lot of steps involved in conducting an experiment. The design process can be a large task in itself depending on the type of experiment. The following list roughly describes the general process that I followed:

- Setting objectives and test requirements
- Develop plan to deliver objectives at a set timescale
- Design and commissioning of experimental setup
- Design of test schedule
- Risk assessment & mitigation
- Operating procedure
- Carry out the experiment
- Analyse the results
- Report

During this specific project I was involved in all the listed steps. This chapter describes the way that I followed these steps for the acoustic validation experiments.

5.1.1 Rig description

The acoustic validation rig consists of an arrangement of ducts. A suitable air mass flow passes through the choking disk at the inlet to the rig to generate a known acoustic boundary condition. By choking the flow the air supply is decoupled from any pressure fluctuations downstream of the choking plane. The air passes through a siren which is used as a noise source. The generated pressure perturbations then travel through a series of proprietary parts and exit the rig. The experimental setup is operated at ambient mean pressure and temperature conditions.

The rig is equipped with two dynamic pressure transducers mounted in the same axial plane. One of these transducers is used as a reference. The other transducer is used to validate three instrumentation port designs for an acoustic rig capable to operate at high pressure and temperature.

5.2 Objectives

The objective of this experiment is to understand and minimise the measurement errors of an acoustic instrumentation port design suitable to measure pressure oscillations in experimental combustion chambers at high pressure and temperature. Hence the experimental setup of a high pressure and high temperature test rig has been used on a controlled acoustic facility where the measurement can be compared to an ideally measured reference signal.

5.3 Design and commissioning of experimental setup

Most of the required parts for the acoustic validation rig were available from previous tests. The various transducer port mountings were new to this rig. The technicians of the test facility were supplied with drawings of the transducer ports and with instructions for rig construction and instrumentation. I was responsible to instruct the technicians about the functional requirements and ensured the transducer ports were ready for testing within the agreed time scale.

5.4 Risk assessment

The rig has never been used with the modified transducer ports. Hence I created a risk assessment for this rig. For any experimental setup it is important to assess the risks that are involved in conducting the experiments and ensure safe rig operation. These risks have to be mitigated before testing can begin. As this is an acoustic test rig the heart of the risk assessment and management was to ensure that noise was kept within suitable levels. The safe level was set at 85 decibels, exposure to anything over 85 dB for a prolonged period of time will create permanent hearing losses.

The mass flow through the siren is affecting the sound levels produced, i.e. the higher the mass flow the louder the produced noise levels. During the commissioning of the test rig the mass flow was increased in small steps and for every step the sound levels in the control room and in and outside the test facility were monitored with a handheld microphone. Even though the sound levels measured in the control room never reached more than 60 dB suitable ear protection was used whenever testing was in progress.

5.5 Operating procedure

The operating procedure is a description of the steps that the operator needs to carry out for every experiment. It describes the start-up of the rig and the setup of the measurement equipment. It also prescribes the procedure to perform a measurement and finally it describes the shutdown procedure. Writing clear operating procedures is very important to enable easy carry-over from one operator to the next and to ensure that the rig is operated safely. This is especially important if the rig is not used very often, the original operator might have moved on and left the company resulting in a lot of additional work.

5.6 Performing the experiments

- Before any experiments can be performed the pressure transducers had to be calibrated and the dynamic data acquisition software system had to be set up with the calibration factors.
- During the experiments the real-time data had to be inspected to ensure the rig is performing as expected. If there are any spurious measurements these have to be corrected accordingly and the effected measurements might have to be repeated.
- I also needed to investigate the signal conditioning equipment and solve some initial electrical interference due to an earth loop in the system.
- During the experiments data integrity and validity must be evaluated.

After the first series of experiments and preliminary data analysis the decision was made to repeat part of the experiments with some minor adjustments to the setup. The frequency increments of the excitation frequency were greatly reduced for improved accuracy. The initial frequency increments did not capture the nodes of the system with sufficient accuracy so I decided to repeat part of the experiments.

5.7 Analysis of the results

5.7.1 Analysis with Fast Fourier transform

The siren is used to create pressure fluctuations. The occurring pressure fluctuations were recorded from both transducers with a dynamic data acquisition system. For every excitation signal the total recording time was set to twelve seconds at a sampling frequency of 12800 Hz. The sampling frequency must be at least twice that of the highest frequency in the signal because of the Nyquist criterion. Experience has shown that an additional margin on top of the Nyquist criterion is required. After recording the data was converted to .mat files to allow further analysis within MATLAB.

The MATLAB routine “analysis_iss3.m”, is used to analyse the recorded data of the first batch of experiments. The time signal is Fast-Fourier transformed with 4096 FFT bins, yielding a frequency resolution of 3.125 Hz. The minimum length of the time signal required for one FFT in that case is 0.32s. The recording time was set to twelve seconds, this makes it possible to fit multiple FFTs into one recorded signal and then perform an ensemble average. The routine does the averaging without overlapping. Every twelve second recording allows for the computation of 37 FFTs. Then the average of these is calculated leading to a time averaged FFT spectrum with improved signal to noise ratios.

The second batch of experiments was analysed using the updated version of the routine, “analysis_iss5.m,” uses 5120 FFT bins. This gives a frequency resolution of 2.5 Hz. The length of the FFT signal is 0.4s and the number of FFTs that can be used for averaging is 30.

The different number of FFT bins and frequency resolution makes it impossible to compare between the first and second set of experiments as the bins and their location in the frequency domain are affecting the amplitude at a given frequency bin. If the same signal is Fourier transformed with a different number of points the result can be very different and therefore should not be compared.

The bin width had to be adjusted because the excitation frequency and the FFT frequencies did not align very well. If the excitation frequency is not close enough to a frequency bin the energy of the excitation signal is smeared out between the neighbouring FFT frequencies.

The signal averaging is a means for reducing the effects of noise in the measured signal. The idea behind this is that influence of random background noise will decrease to zero as the number of averages tends to infinity.

The FFT transform assumes that the measured signal is exactly one period of a periodic signal. In reality this will not be the case. Because of this a discontinuity will occur at the endpoints of the signal. The FFT transform of this signal with a discontinuity will show a peak around the main frequency of the original signal but will also show high side lobes at neighbouring frequencies. This is called spectral leakage. These side lobes are actually caused by the discontinuity that is introduced by the finite measurement and does not represent a physical phenomenon.

To compensate for this effect the original time signal can be conditioned by using a windowing function. The windowing function decreases the amplitude of the signal near the endpoints to decrease the influence of the discontinuities at the endpoints. Basically the windowing function is zero outside of a certain interval. Inside this interval the signal is modified towards the endpoints. The way the signal is conditioned towards the endpoints depends on the windowing function that is applied. In this case a hamming window was used. The hamming window makes the endpoints of the signal match up 92% closer, see Figure 5.

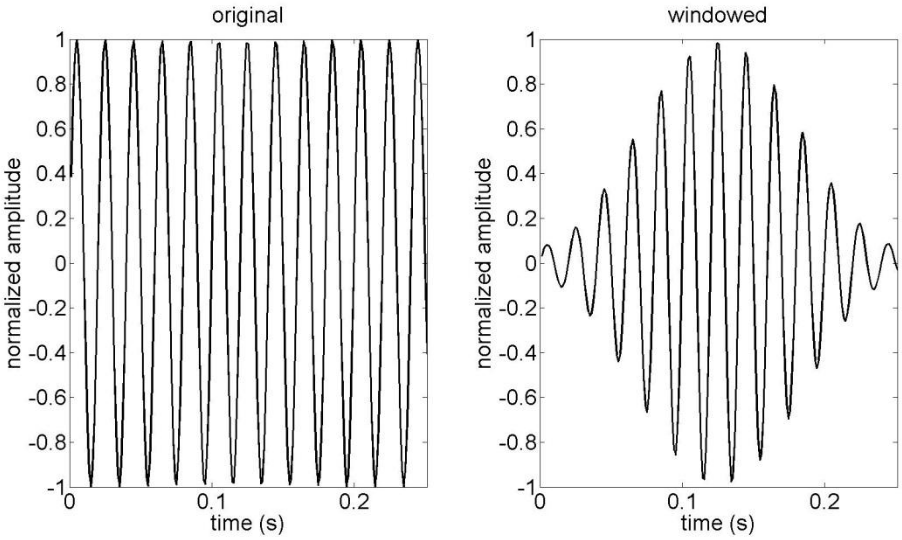

Figure 5 - Example of sine wave with and without windowing.

The drawback of using a windowing function is that it will decrease the amplitude of the signal and thus will decrease the energy content of the signal. It can be shown that after applying the hamming window 54% of the original amplitude remains in the signal. To correct for this loss in amplitude the windowed signal is divided by 0.54 thereby restoring the energy content to the original value. The energy content is restored to that of the original signal but the endpoints are tapered towards zero. This way of applying a window will decrease spectral leakage but preserve the energy content of the original signal.

The MATLAB routine (iss3) creates two folders with MATLAB and jpg figures and creates an excel file with a summary of the project. The two output folders are called “jpg files” and “fig files”. The routine creates a copy of the frequency and time domain figures in each folder in the corresponding file format. In the project summary excel file the routine stores the siren excitation frequency, the amplitude, phase difference, coherence and amplitude difference. It also stores these data for three multiples of the original excitation frequency.

5.7.2 Calibration and results

An additional routine “calibration_iss2.m” is be used to calibrate the dynamic data acquisition system (DAQ). The DAQ is connected to a scope and a function generator. The objective of this is to check if there any signal losses within the DAQ that require correction. In addition to the calibration of the DAQ system the pressure transducers and the line amplifiers also needed calibration. There are losses associated with the line and the signal conditioning equipment that change the signal. The signal passes through a galvanic separator and a signal amplifier. The line calibration was conducted by Rolls-Royce technicians. They provided the calibration coefficients that needed to be entered into the data acquisition software. The initial results showed that several pressure nodes were present in the system. The signal to noise ratio at a pressure node is poor, as the pressure amplitude is p’=0 Pa. Therefore the data at these nodes has been removed before any further analysis was done.

The amplitude spectra obtained with the MATLAB routine are compared between the three different geometries that were tested and they are compared to reference probe signal. The routine exports the values of various variables at the siren excitation frequency to excel for further manual analysis. The amplitude deviation is transformed to a percentage to make comparison between the different geometries possible. This has been done using equation (1).

$$\varepsilon = \frac{|\hat{p}|_{geometry\,1,2,3}}{|\hat{p}|_{reference}} * 100 \quad (1)$$

The phase difference of the investigated geometry relative to the reference probe was calculated by taking the angle of the cross power spectrum. Equation (2) shows the definition for the cross power spectrum as it was implemented in the analysis routine.

$$G_{12} = \frac{FFT(2) \times \overline{FFT^{*}(1)}}{n^2} \quad (2)$$

Equation (3) shows the definition of the Coherence as it was implemented in the analysis routine. The coherence is a number between zero and one. In this case it indicates if the transducers are measuring the same signal. At the excitation frequency the coherence must be very high (C_{12}>0.99) to make comparison of the result valid. At the excitation frequency both transducers read the pressure perturbation from the siren. The results show that all the signals show good coherence at the excitation frequency.

$$C_{12} = \frac{|G_{12}|^2}{G_{11}G_{22}} \quad (3)$$

5.7.3 Scaling of results

The objective of this experiment was to validate the transducer port design on a high temperature and pressure rig at ambient conditions. It is therefore important to scale the experimental results at ambient condition to the operating conditions as they are found on the high pressure and temperature rig. The measured experimental error due to the test setup has been scaled based on the changes to the speed of sound between ambient and high temperature conditions.

5.8 Conclusion

The performance of the three different transducer port designs was judged based on the amplitude deviation, phase deviation and the coherence relative to a reference signal. The geometries and the conclusions are proprietary and hence have not been shown. The results from these experiments were very interesting and have led to very valuable insights into the acoustic behaviour of the investigated geometries. These results have affected the design of the actual application at high temperature and pressure.

6 Experimental: Altitude relight facility

6.1 Introduction

6.1.1 Rig description

The Sub Atmospheric Relight rig, in short SARS, is a steel pressure vessel that houses two fuel spray nozzles and holds a twin sector combustor arrangement. This rig can run with a great variety in operating conditions. It can be build up to run at sub atmospheric pressures with low temperatures simulating altitude relight condition at 30 000 ft. and it can be modified to run at elevated pressures and temperatures. The test section that houses the combustor is shown in Figure 6, the test section can be build up with different combustor arrangements and fuel spray nozzles. Altogether this makes SARS rig a very unique and flexible experimental setup that is used for a lot of different experiments.

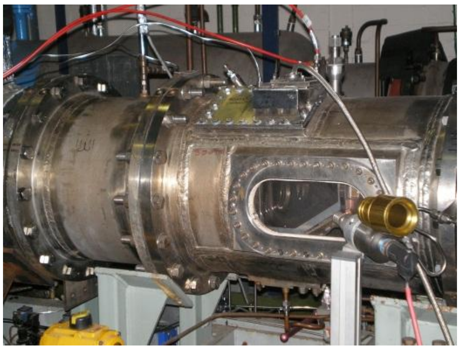

Figure 6 - Test section of the SARS rig

The rig is equipped with various thermocouples and pressure transducers. All of these are monitored with the computers in the control room. Furthermore the test rig has optical access for cameras and various laser measurement techniques.

6.1.2 Sub atmospheric relight

In sub atmospheric operation the pressure on the rig is reduced to about 6 psi and the inlet temperature is reduced to around 265 K. This simulates the conditions that a jet engine would experience at high altitude after flameout. The objective of these experiments is to establish the altitude where the combustor and fuel injector combination is still able to achieve successful relight. The altitude that a jet engine must be able to light follows from requirements by the airframe manufacturers, i.e. the customers of the jet engine supplier. Inside this envelope the jet engine must be able to relight in the event of a flameout at altitude. The ability to achieve relight for a given engine geometry is assessed on the basis of combustor mass flow and the combustor FAR. The combustor mass flow is related to the forward speed of the airplane and to the engine characteristics.

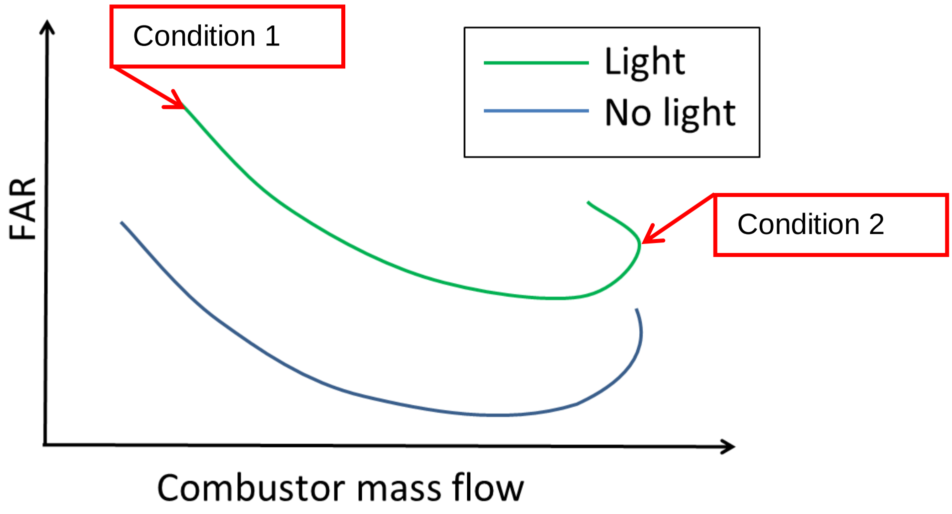

Figure 7 – Typical relight loop from SARS rig

In Figure 7 an example of a typical relight loop is shown. On the SARS rig the operating conditions and the combustor mass flow are set to the desired values. Once they are achieved the fuel flow is engaged and the igniter is enabled. Altitude ignition is a stochastic process and the light and no light lines are defined by detailed experimental procedures with multiple attempts at a given ignition point.

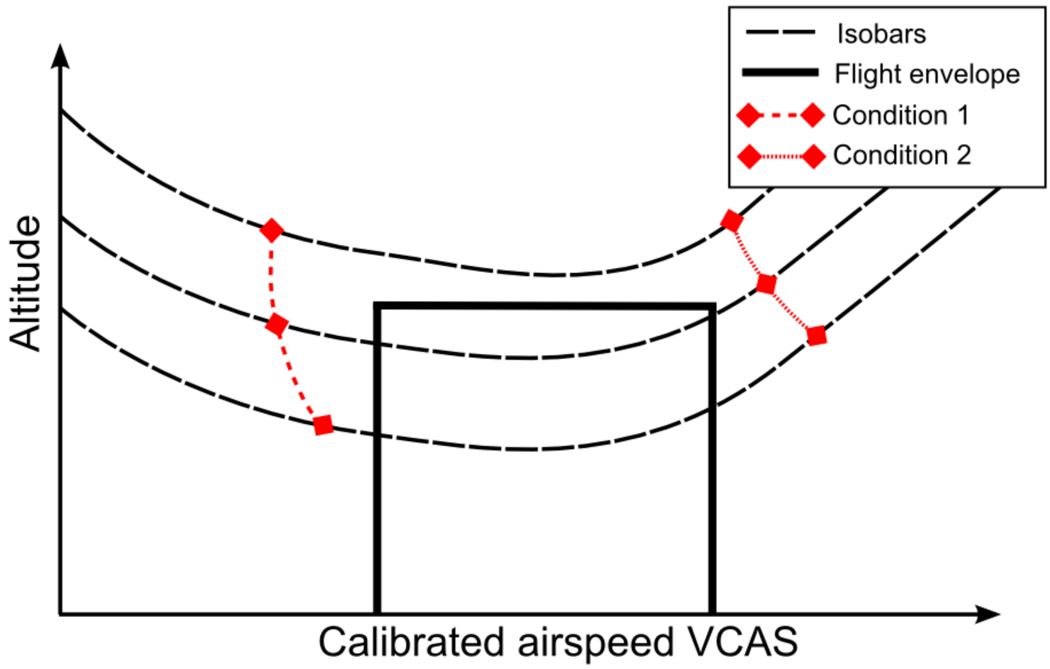

Figure 8 – Typical light envelope

In Figure 8 a typical flight envelope for a subsonic turbojet is shown. Inside the flight envelope box the engine must be able to relight to meet the airframe manufacturer's requirements. The combustor mass flow is related to the calibrated airspeed (VCAS) and to the engine characteristics. Hence the location of condition 1 and 2 from the relight loop can be superimposed onto the flight envelope box. In Figure 8 the results for three relight loops at three different pressures are shown. If all these points lie outside of the flight envelope box the fuel injector meets the manufacturer's requirements.

6.2 Objectives

For this series of experiments there are two objectives. The first is to determine the effect of combustor geometry on relight performance. Three different combustor geometries have been used with three different fuel spray nozzles. The second objective was to determine the repeatability of the results obtained with the SARS rig. This was investigated by repeating some of the previously measured ignition data that was already available. This helps in determining if the facility is giving repeatable results and determines the accuracy of the measurements

6.3 Design and commissioning of experimental rig

The rig build on the SARS facility is highly procedurised. However I was responsible to develop a test plan for the various hardware components and I interfaced with the technicians to ensure that testing was able to occur at the agreed time scales.

6.4 Risk mitigation and Operating procedure

The risk mitigation and operating procedure for this test rig were already in place.

6.5 Experiments

The operation of this rig is fully automated, however because of the optical access and the evaluation of the video recordings I have gained great insight into gas turbine combustion. This experience gave me a first understanding of actual flame shapes and unsteady combustion characteristics during the ignition process. The experimental work and the inherent problems that accompany it have given me a good appreciation of the challenges involved in meeting altitude relight requirements. It is equivalent to lighting a fire in a storm on the top of Mount Everest.

6.6 Analysis of the results

To analyse the results a comparison is made between the 18 relight loops that were measured. It is important to look at the location of conditions 1 and 2 and to look at the overall location of the loop. To objectively compare the difference in condition 2 between the different experiments equation (4) is used. This equation calculates the difference between the actual and the average as a percentage. The same equation is used on the back to back testing points. This yields the average accuracy to which the location of condition 2 can be determined with this rig.

$$\varepsilon = \frac{\dot{m}_{geometry\,1,\ condition\,2} - \dot{m}_{geometry\,2,\ condition\,2}}{\frac{1}{2}\left(\dot{m}_{geometry\,1,\ condition\,2} + \dot{m}_{geometry\,1,\ condition\,2}\right)} * 100 \tag{4}$$

6.7 Conclusion

It was found that the location condition 2 could be reproduced to the required accuracy with the SARS rig. It was also shown that one of the combustor geometries was showing a consistently better performance across all of the experiments. The difference was significantly larger than the accuracy that was determined earlier on. In this way sensitivities of the combustor geometries to the relight performance were identified.

7 References

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