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ACTIVE CONTROL OF COMBUSTION AND ITS APPLICATIONS

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ABSTRACT

The ducted flame in any of its forms can have the tendency to interact with its surroundings. When this interaction takes the form of thermo-acoustic instabilities the consequences can be grave. These instabilities have been recognised as a problem for many decades and have appeared in many forms of engine including rocket motors, ramjets, main engine gas turbine combustors and after burning systems.

It is true to say that the phenomena has not been truly understood and that many researchers have come up with several theories as to how these thermo-acoustic instabilities occur. In the field of engineering, the ability to fix the problem rather than fully understand the problem has been a principle that has been applied for many years. The approaches taken to fixing thermo-acoustic problems have been either radical re-design of the combustion system or the application of passive damping techniques. In the past decade, however, a further technique has been given to the combustion designer, that technique being the ability to use active control.

This paper outlines how the technique has been developed, from small scale pilot rig testing through to full engine demonstration, and how active control may be applied to land-based gas turbines in the future. With the introduction of ultra low emission lean pre-mixed combustion systems to land based gas turbines the propensity to exhibit thermo-acoustic instabilities has increased. Actively controlling the instability is a real option, the benefits of gaining extensive experience with the technology on land will help to promote the technology for future application to aircraft.

1.Introduction

The problem of combustion instability has existed since flames have been confined within ducts. They occur in many types of combustion system from domestic heating systems through to rocket motors and gas turbines. The instability can manifest itself in a number of different forms from relatively simple longitudinal waves to highly complex spinning structures. The way that the instability interacts with its surroundings may well be an annoyance to an operator of that system. Alternatively the instabilities could cause catastrophic mechanical failure of the combustion system or its surrounding. Neither of the above are acceptable the latter more so than the former and it has been the job of the combustion designer to lessen the effects of combustion instabilities. Within the designer's toolbox there are three methods of controlling the instability should it occur. The first two of these methods has been around for a considerable time, that is the use of so called passive dampers. As the name implies the device modifies the overall damping of the system either by means of an acoustic liner or helmholtz cavity, or by modification of burner aerodynamics which modifies the reaction zone/ sound field interaction. In practice the above techniques rely on knowledge of the transfer function across the flame and the properties either side. These are rarely known and hence there is always a degree of cut and try with this approach. The third method used to control instability is the use of active control and it is the main objective of this paper to describe how such a method has been developed through a laboratory scale experiment through to a full gas turbine demonstration of the principal.

2.Background

It is well known and often quoted that combustion instabilities occur due to the interaction between unsteady heat release from the combustion process and acoustic waves. Rayleigh[1] described the above in a clear and concise way.

According to Rayleigh[1] the amplitude of a sound wave will increase when there is heat addition in phase with its pressure. If on the other hand the heat is added out of phase with the pressure there will be a reduction in amplitude. In accordance with Dowling[2] for a simple combustor such as a Rijke tube where there is no mean flow equation (1) can be used as a generalised form of Rayleigh's criterion, ignoring viscous effects. The equation says that if the energy (left hand side) is greater than the surface loss term (right hand side) then the disturbance will grow.

$$\int_V \frac{(\gamma-1)}{\overline{\rho c}^2}\overline{p'q'}\,dV > \int_S \overline{p'u}\cdot dS \qquad (1)$$

where ρ = density
c = speed of sound
p = pressure
u = particle velocity
γ = ratio of specific heats
q = heat release/unit volume
V= volume
S= bounding surface

The overbar denotes an average over one cycle and the prime denotes a perturbation.

It had been demonstrated that active control could be applied to relatively simple geometries such as a Rijke tube in the early to mid 80's, Dines[3]. Using the principal that equation (1) can be manipulated, for effective

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control the inequality in the equation has to be reversed. This can be done by either increasing the losses at the boundary (right-hand side) or by decreasing the energy source term (left-hand side). Dines[3] eliminated the noise emanating from a Rijke tube, which had a laminar flame burning on a gauze. A loudspeaker near to one end of the tube was driven in such a way that it modified the acoustic energy lost on reflection. The phase of the oscillation was detected by measuring the light emitted by CH radicals in the flame. This signal was filtered through a narrow band filter, then phase-shifted and the signal amplified and used to drive the loudspeaker.

The experiment was repeated by Heckl[4] only in this case the light emission photo-multiplier was replaced by a microphone as the detector. What this work demonstrated was that stability could be achieved over a range of phases and that the imposed phase delay is not crucial to the performance of the controller.

3. Cambridge Buzz Rig

Having seen the success that had been gained in controlling the simple Rijke tube combustion system, a small combustion test facility was built that would anchor turbulent flames in a similar fashion to those in afterburners. This facility became known as the buzz rig. The rig consisted of a bluff body flame stabiliser mounted in a 70mm quartz tube, the dimension of the flame holder gave a similar blockage to that seen in the afterburner of a gas turbine. The facility ran on a blowdown air supply that would allow for adequate stable air supply for 20 minutes. The unit was supplied with ethylene as a fuel and the total thermal output of the rig being circa 0.25 MW.

Results were gained from this unit using two different modes of active control. The first mode of control was a device as shown in fig.1. This allowed for the inlet boundary to

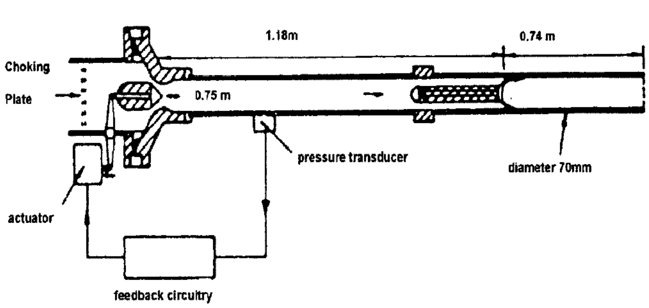


Fig. 1 Cambridge Buzz Rig – moving plug

the rig to be modified. Bloxsidge et al[5] reported this work, typical results from this rig are shown in fig. 2 and 3.

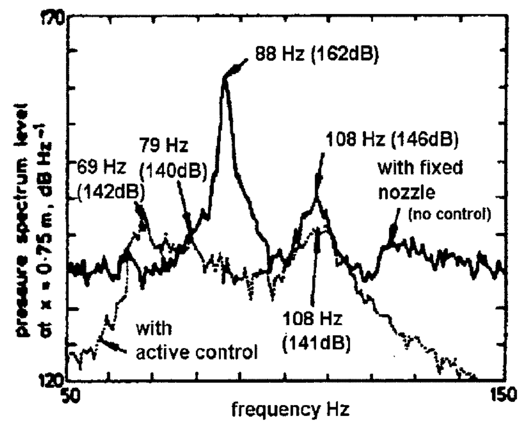
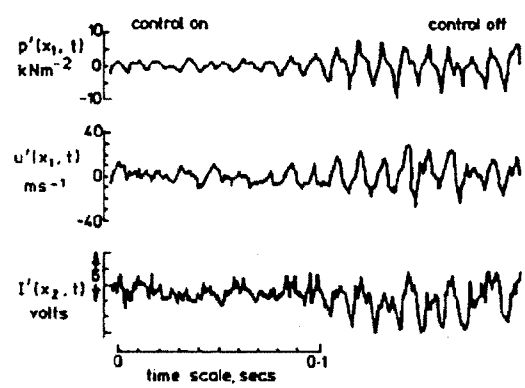


Fig. 2 Effect of control on pressure spectrum

Both figures show the effect on the pressure spectrum with and without control being applied.



p': unsteady component of pressure
u': unsteady component of axial velocity
I': unsteady component of light emission

Fig.3 Time history when control is cancelled

It can be clearly seen that there is a 21dB reduction in the peak and it was reported that in the frequency range 0-800 Hz a 90% reduction in acoustic energy was observed. In fig. 3 the pressure, axial velocity and light emission histories are plotted when the controller was turned off; the increases are clearly apparent.

The geometry as presented in fig.1 cannot be incorporated in any practical gas turbine afterburner design; an alternative technique of achieving control was explored. As shown in equation (1) modifying the energy balance at the boundary of the system is only one technique. The other method is to apply modification to the combustion and acoustic energy, this was done by the unsteady addition of fuel.

The rig shown in fig. 4 is the same as that shown in fig.1 but modified to fix the inlet boundary. The rig also has an additional plane of fuel supply. This secondary fuel supply was located to give minimal delays.

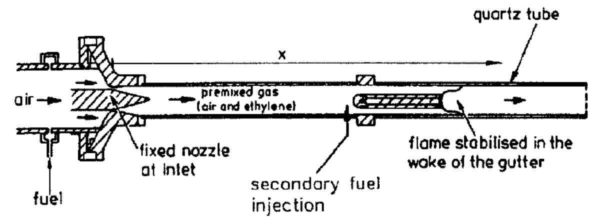


Fig.4 Cambridge Buzz Rig – modified unsteady fuel.

The secondary fuel was delivered to the unit via 4 off automotive fuel injectors, in order that the fuel did not appear as 4 rich streaks at the flame front secondary air was premixed with the fuel prior to delivery through 24 equi-spaced holes on the wall of the rig.

The result of this work is described by Langhorne et al [6,7]. The principal results from this rig are shown in Fig. 5 and 6.

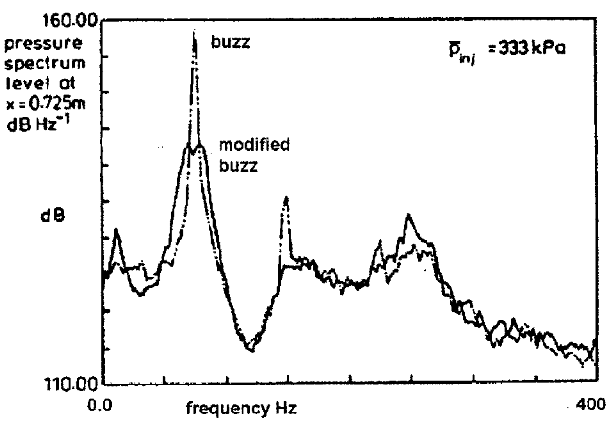


Fig. 5 Effect of control on pressure spectrum

Again it can be clearly seen that the control strategy applied to the rig has had a significant effect. The peak has been reduce by 15dB when the controller is in operation. The amount of fuel pulsed was an additional 3% of the total fuel supplied to the rig. The effect of switching the controller off on the combustion system is shown in Fig.6

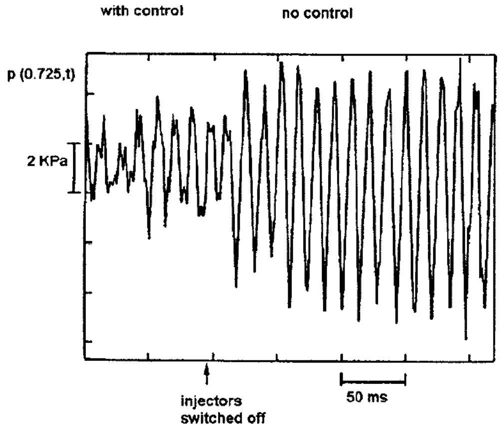


Fig. 6 Time History when the controller is cancelled.

4 Full Engine Demonstration

In 1988 having seen the very encouraging results that the Cambridge rig was delivering with regard to the ability to control combustion instabilities it was decided that a full engine demonstration should be carried out. The choice of test vehicle for the demonstration was the RB199 engine. This engine was chosen because its buzz characteristics were extremely well known and at that time the newer product such as the technology demonstrator engine XG40 and the EJ200 were less suitable because their characteristics were not as well developed. The older engine types such as the Spey and Adour did not have engine control systems that would lend themselves to this type of work.

The engine demonstration would bring more degrees of complexity than had been previously encountered on the Cambridge rig, the engine had multi-stream fuel in the afterburner, with 3 streams namely a core stream, a bypass stream and a primary stream. The proposed demonstration however would only look at the core and bypass streams, the primary fuel flow being a relatively small amount when compared with the other two. Also the function of the primary is to pilot the combustion process and therefore changing its characteristics may seriously diminish its operability.

It was proposed that fuel modulation be the preferred method of control as this was by far the easiest engineering solution. Unlike the Cambridge experiment fuel would be spilled from the engine as opposed to being added. There were two good reasons for doing this. The plot shown in Fig. 7 is a typical thrust boost characteristic for a high bypass ratio afterburning engine. The RB199 already uses passive control to get it into the high thrust boost regions, Henderson et al[7]. The addition of more energy in the form of fuel in the region where it is buzz prone would have little effect, because the curve of thrust boost is approaching a plateau, reflecting the change in energy. Therefore the removal of fuel from the system is more desirable as it takes the system into the steeper part of the thrust boost/fuel air ratio slope hence small changes in fuel flow have larger effects on heat release. The second reason for removing fuel was the ease of engineering. Addition of fuel would require external fuel pumps and bleed in valves. This option may well have interfered with the engine control system due to changes to the volumetric flow rate / pressure/ flow number relationship.

The fuel modulation was achieved by the use of high response electro-hydraulic servo-valves. It was realised that the application was on the limit of where actuator technology lay at that time and to a greater or lesser extent where it is today. It was known that during operation the valves may have to be cycled up to 120 Hz and that they might be required to pass upto 15% of a streams flow rate. This was recognised as a challenge.

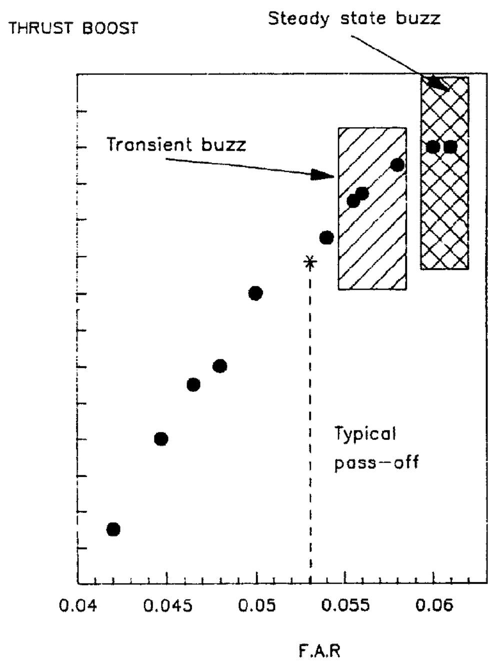


Fig. 7 Typical thrust boost vs. F.A.R

The programme was set up with 3 main phases to the work:-

- Fuel rig testing of the servo-valves.
- Establishment of jet-pipe response to pulsation over a range of spill flows and frequencies.
- The demonstration of active control, using the knowledge gained from the forcing experiments.

The valves used were Dowty high response servo-valves. These valves were subjected to a full range of dynamic and steady-state characterisation tests. As part of this test programme it was also desirable to know if there would be any unwanted side effects on the RHFCU (reheat fuel control unit) or on the fuel pumping system.

This phase of work was successfully completed and the valves were fully characterised. This confirmed that the valves would pass the flow and give frequencies to levels consistent with the programme requirements. One of the major side effects noted was that the engine fuel pump would produce 'noise' at undesirable levels and frequencies. In order that this would not feedback into the experiment the noise was damped by the installation of a pulsation damper in the fuel feed line between the fuel pump and the fuel distribution skid. The pulsation damper used was a commercially available bladder type accumulator. Whilst continually cycling the fuel spill valves it was also noted that large fluctuations in manifold pressure were observed similar in nature to water hammer. This was more than likely an artefact of the manifold/jet-pipe simulation used, however this was taken into account in the methodology applied to characterisation of the engine.

The engine test took place on an atmospheric engine test bed at DERA, Pyestock. The engine used was an RB199-04C, the engine was modified to accept the special fuel lines required for addition of the fuel spill valves. A schematic diagram of how the spill valves were implemented is shown in Fig.8.

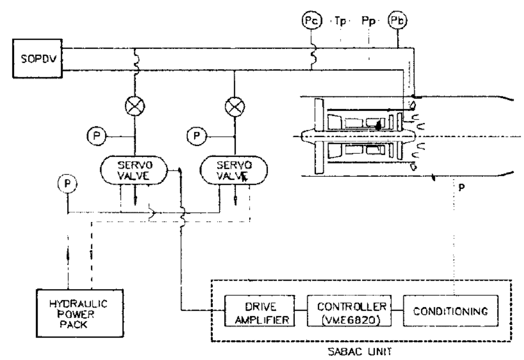


Fig. 8 Layout of spill system

The engine was also modified to include an off engine pallet mounted fuel and final nozzle control unit. This unit known as the Lucas 'fast-reheat' system obviated the need for the engine mounted main engine and afterburner Fuel Control Units (FCU's). A hydraulic power pack was required to provide power for the final nozzle actuation and for the driving of the servo spill valves. In Fig. 8 the configuration of the hardware for the active control can be seen. The feedback-input loop was from a Vibrometer CP102 type transducer, this type of transducer is standard on this engine and it measures the unsteady pressure in the jet-pipe. The output loop was to the Dowty 6-port servo valves as previously described. The unsteady pressure signal was taken into the SABAC unit via a conventional charge amplifier. The SABAC unit consisted of input signal conditioning, a processor unit and current drive outputs.

The active control logic was relatively simple and is shown diagramatically in Fig. 9. The filtered pressure transducer signal X is taken into the processor where it is compared with a preset value XT (threshold). When the signal exceeds the threshold level, the processor times the period of the transient, then outputs a drive signal of the same time period but with an appropriate time delay PHI and pre-defined amplitude DEL. The XT, PHI and DEL are all tuneable so that the user could input them in to the SABAC unit.

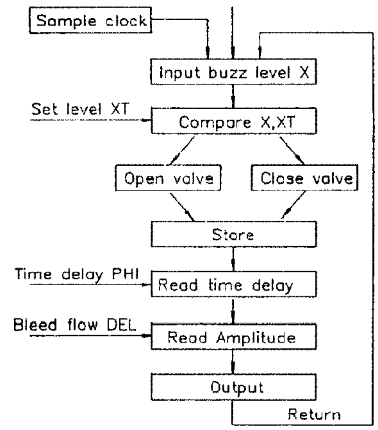


Fig. 9 Spill control programme Operation

The intended relationship between the input signals, threshold and the output signals are shown diagramatically in Fig. 10.

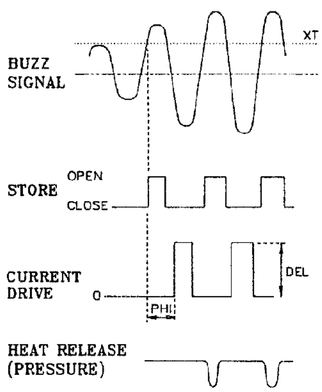


Fig. 10 Spill control function

It was important to understand how the combustion system would respond to being forced, that is no control on but stimulation of the system by pulsing fuel at different degrees of spill and at different frequencies. The transfer function of the system could then be determined from the forcing tests. Due to the experiences in the first phase of the programme where large fluctuations in manifold pressure were observed when the spill valves were subjected to continual sinusoidal motion, the response of the jet-pipe to stimulation was by a single dip in fuel flow of varying amplitudes.

The results of stimulating the combustion system are shown in Figs. 11 and 12. The response in the jet-pipe to a dip in bypass fuel flow is shown in Fig. 11. The demanded fuel flow reduction was circa 10% of the total flow for that stream the combustion delay time is of the order of 14 ms.

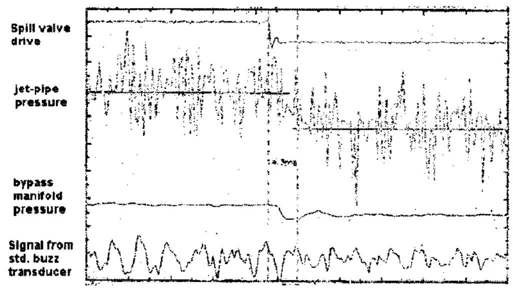


Fig.11 Fuel dip in bypass stream

When a similar magnitude fuel dip was applied to the core stream Fig.12. It again shows that the time delay was of a similar magnitude to that of the bypass stream 14 ms. From the data recorded from the engine it was apparent that the fuel spill from the bypass stream was more effective than that of the core stream at producing a larger effect on the jet-pipe pressure for an equivalent fuel dip.

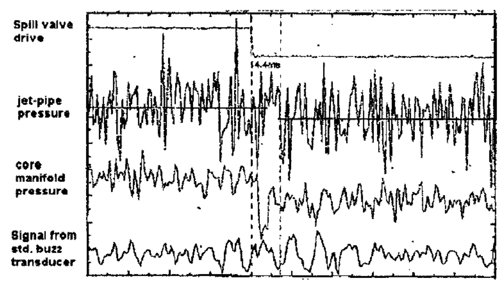


Fig. 12 Fuel dip in core stream

Because of time constraints the demonstration of active control was only given by the use of modulation of the bypass stream fuel.

Having determined that the system would react to a stimulus of dipping fuel the next part of the exercise was to now demonstrate active control. The demonstration took two different forms, running the engine up to a point where the engine protection system would chop the afterburner fuel due to excessive noise, then repeating the point to the same condition with the controller in use, this procedure was called "buzz-limiting". The second method was to have the controller on and then switch it off and monitor the system until the natural engine protection system shut the afterburner down.

An example of the former is shown in Fig. 13 and the latter in Fig. 14. It can be seen in Fig. 13 that the spill valve drive signal is operating only when it is required. When there are quiet periods i.e. the noise is below the set point no action is being taken by the device. The demonstration on the engine was carried out with spill flows between 5 and 10%

valve drive signal is operating only when it is required. When there are quiet periods i.e. the noise is below the set point no action is being taken by the device. The demonstration on the engine was carried out with spill flows between 5 and 10% and with time delays of 9.0 and 3.4 ms. The system showed adequate control over all of the conditions. The threshold at which the system was triggered was also changed within the range ± 1.0 kPa to ± 0.67kpa again adequate control was shown but there was not enough time allowed for an exhaustive look at the control parameters and to allow for a high degree of tuning to take place.

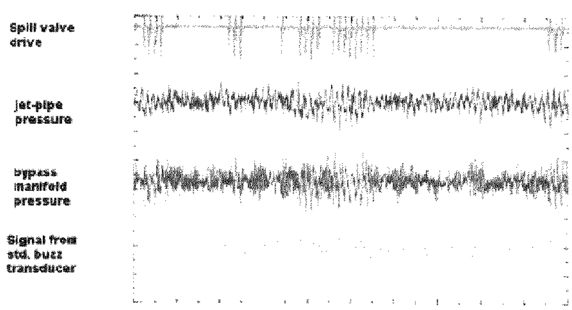


Fig.13 Steady state operation with active control

It can be clearly seen in Fig. 14 that when the controller is switched off, signified by no spill drive signal, that the unsteady pressure in the jet-pipe increases. The event is then terminated by the engine health monitoring system cutting the afterburner fuel this is signified by the reduction in bypass manifold pressure. In all of the events that were carried out like this the buzz amplitude grew to a maximum within 15 cycles of the chop event.

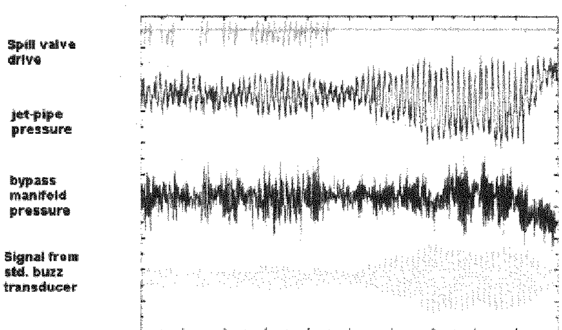


Fig 14 Cancellation of active control

In summary active control has been demonstrated satisfactorily on a full-scale military turbofan engine. The correlation between what happened on the small-scale rig and the engine was good. This is demonstrated in Fig 15, where it can be seen the reduction in the peak buzz frequency on the engine was 11.7 dB which is comparable with the 15.5 dB measured on the small-scale rig. If further time had been available maybe further reductions could have been made. It is true that with todays improved control logic that improvements would be gained over the extremely simple logic applied at the time of the demonstration.

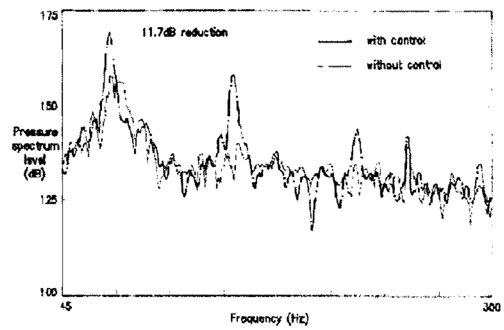


Fig. 15 Best result from the engine testing

5.0 The Future

The strive for ever lower emissions from industrial gas turbines and the control technology being applied by most engine manufacturers namely lean premix combustion is increasing the propensity to have instability problems. In some cases the lowest achievable emissions for the system cannot be achieved because of instability. The industrial RB211DLE system shown in Fig. 16 like all systems has seen some difficulties with combustion related noise. Unlike the afterburner the chances of seeing noise from one engine build to another varies i.e there are quiet engines and there are noisy engines.

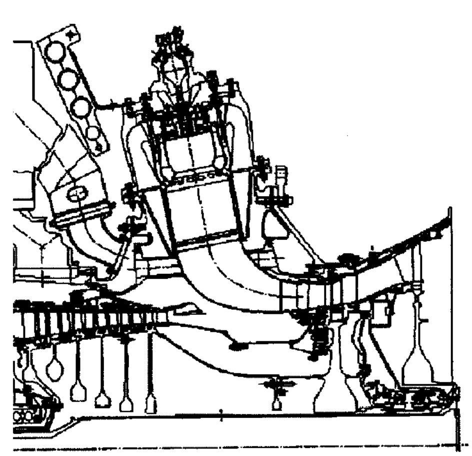


Fig. 16 Industrial RB211DLE

There are no features within manufacturing tolerances that can be picked up to tell which combustors will have a applied to afterburners have also been used to good effect on the industrial systems Willis et al[8], however there are on occasions difficulties.

A typical noise map for an RB211-24G engine is shown in Fig. 17. The map shows the temperature in the primary and secondary combustion zones, the secondary temperatures can be read as power. The plot shows regions of noise islands and the amplitude. On a quiet engine there is a space between the 'D' and 'E' islands. It is conceivable that active control could deliver engines that will always be quiet.

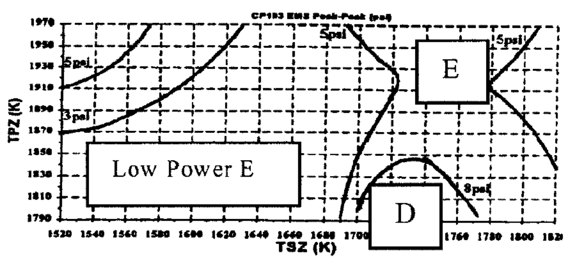


Fig. 17 Typical Noise Map for an RB211-24G.

The difference between the industrial unit and the military turbofan is the frequencies are very much higher 500 to 700 Hz. This poses problems in that current actuator technology can only operate at up to 250 Hz. Further work on actuators is essential for the technology to progress. The reliability of the servo-valves used in the afterburner case may be called into question if used for an industrial use. The normal life between overhauls on industrial engines is circa 24000 Hrs, if the valve is in use for only a fraction of that time it is not inconceivable that the valve could reach 10^{10} cycles which is outside the range of this type of device.

There are industrial units that are applying active control, Seume et al[9] ,Hoffmann et al[10], but these units exhibit lower primary frequency combustion instabilities <250Hz and therefore use current actuator technology.

6.0 References

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PAPER -2, A. J. Moran

Question (S. Candel, France)

In your experience, have you found a way to shape the signal of the fuel line to achieve optimal response?

Reply

There was a degree of shaping during the valve characterization. This was done to try to overcome a water hammer effect seen at that time. When the engine test was carried out, no shaping took place.

Question (A. Annaswamy, USA)

What is the role of more complex active control strategies?

Reply

Valve technology has to be improved to cope with high frequency instabilities and the control has to be appropriately designed.

Question (W. Proscia, USA)

Is most of the 14 ms delay that was measured attributable to fuel line transport delay from the valve to the injector?

Reply

Virtually all of the 14 ms is the transport time from the fuel injection point to gaining detectable heat release.