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FORCED COMBUSTION EXPERIMENTS ON AERO COMBUSTORS

Nick Pilatis
Rolls-Royce plc
Derby, England

Michael Whiteman
Rolls-Royce plc
Derby, England

Paul Madden
Rolls-Royce plc
Derby, England

Michael. A. Macquisten
Rolls-Royce plc
Derby, England

A. John Moran
Rolls-Royce plc
Derby, England

ABSTRACT

In the world of gas turbine combustion there is always the spectre of thermo-acoustic instability. Over the past few decades there has been significant effort afforded to researching the phenomenon of thermo-acoustics. The results of the research have produced numerous mathematical models and at system level these models have been used to predict and post-dict where noise is likely to occur in a given system. The models also allow the combustion system to be numerically tested through the flight or operational envelope to identify areas where instability may occur before testing is carried out, thus reducing the risk of unexpected noise occurring. The weakness of many of these models is that they require, what is known as a flame transfer function. The flame transfer function is normally measured after the combustor has been fully designed and at a high TRL (Technology Readiness Level) so significant investment in time and money are already baked into the design. Remedial action if required can result in a significant loss of time and money in the development of the combustor. This paper describes the design and use of a test rig that allows combustion systems to be tested at much lower TRL.

A ‘siren’ rig has been developed and used to identify what particular design changes in either combustor flow field or fuel delivery systems have effects on the thermo-acoustics. The exit boundary of the unit has a representative choked end point. This end point has the ability to be modulated in time, thus forcing the whole system. How the system reacts to the forcing is measured over a range of frequencies. The rig has been successfully used to influence design changes required to avoid combustion driven oscillations within the next generation of aero gas turbine combustors. The rig is not a representation of a complete 360 degree annular combustor system, but of a smaller sector. The objective is to isolate the Fuel Spray Nozzle (FSN) and corresponding combustor sector from acoustic resonances and derive functions expressing the relationship between unsteady heat release rate and unsteady aerodynamics for a range of operating conditions by controlling the modulation of air mass flow rate. Such functions can be used in conjunction with acoustic linear theory to predict wave modes and growth rates in combustor geometries.

1 INTRODUCTION

Gas turbine combustion systems like many other ducted combustion systems can suffer from the phenomenon known as thermo-acoustic instabilities. When these instabilities manifest themselves in real combustion systems they can at worst cause severe mechanical failures of the combustor or surrounding hardware, or over time lead to significant wear problems. The mechanisms are well known and have been well documented in the past with numerous academic and industrial based papers written on the subject. There has been significant effort given to the modelling of combustion instabilities and in the past few years these modelling efforts have become mature in nature. This being said the modelling capability for a new design of combustion system still firmly remains in the postdictive regime rather than in the predictive regime. The main reason why this is the case, is that a lot of the models require knowledge of how the system will reacts to perturbations, in control system language the transfer function.

In the past testing of combustion systems at low TRL have often shed little or no light on the thermo-acoustic behaviour of a combustion system. Only when the system has been tested at higher TRL, with much of the real architecture and scenery around the combustor have some problems been brought to the attention of the engineering team. When a thermo-acoustic problem appears late in the development of any combustor the costs in both time and delays to engine development programme plus cost overruns can be significant.

Therefore a tool that can identify changes to either fuel injector hardware or combustor stoichiometry in the early part of a system development will be of significant use. Such a tool that can deliver the transfer function of a system that allows the modelling system to probe the design space over the whole of the flight, or operational envelope would be very useful to the engineering team. It is well known that by changing the boundary conditions within the combustor such as modulation of the fuel with the appropriate time delay (see references 1 to 6) that the system can be brought out of resonance into a more stable acoustic regime. This modifies the cycle as described in figure 1. There is a requirement for a facility that can modify unsteadily and controllably the boundary conditions of the combustor in order to measure the dynamic response of the total system. Examples of a number of these types of rigs are cited in references 7 to 11. As described in many of the aforementioned references a siren type facility could very well be such a tool. A programme of work has been embarked upon to develop a siren rig that could be used to probe different aspects of a combustor design and to ascertain what changes in combustor hardware design will affect the thermo-acoustic behaviour.

NOMENCLATURE

K = constant of transfer function
ω = angular frequency ($=2\pi f$)
τ = the time delay
q = the heat release rate
m = mass flow at the injector
^ and – denote unsteady and mean averaged variables
k = wave number ($=\omega/c$)
L = distance between injectors and siren
f = frequency
fres = resonant frequency
Δf = half power bandwidth
TRL = Technology Readiness Level (NASA)
$T(\omega)$ = flame transfer function
TRL = Technology readiness level
p = pressure

2. THEORY

Thermo-acoustic instability in gas turbine combustors is the result of the interaction of what can generally be described as three processes, namely, unsteady aerodynamics, unsteady heat release rate and combustor acoustic resonance; see figure 1. When the conditions are favourable, large amplitude self-sustaining pressure oscillations can occur, references 12 - 16. To assess the propensity to such instability, it is common practice, in the design stage of a combustor system, to carry out bespoke tests. Within these tests the unsteady aerodynamic and heat release processes are separated from those of the acoustics of the combustor. These are studied in an acoustically controlled environment under the action of a forced flow field; see figure 2. To generate a periodically varying pressure field a “siren” is commonly used. This device generates a wide range of acoustic signals, which are independent of the acoustics of the combustor; see figure 3. This enables a complete characterisation of the unsteady coupling between combustor/injector aerodynamics and heat release rate and the derivation of so called “Flame Transfer Functions”. These transfer functions are used within a linear perturbations model of the geometry to predict wave modes and growth rates in combustor geometries.

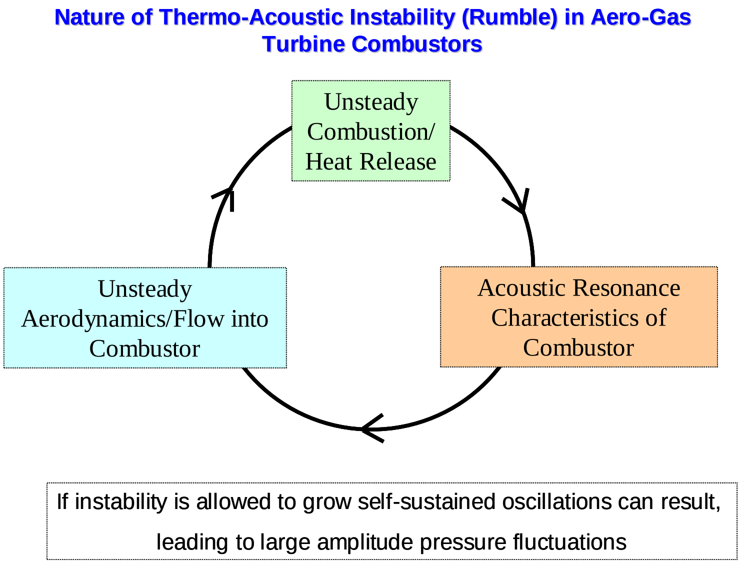

Figure 1 A thermo-acoustic cycle.

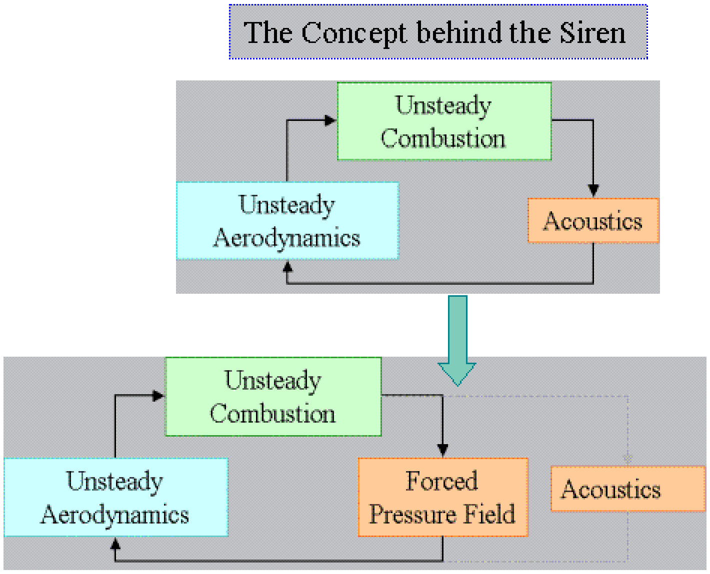

Figure 2 Concept of the siren.

3. CONCEPT RIG

In order to design the Siren rig a number of upstream and downstream modulation system were considered. It was felt that having direct control of the modulation of the combustor pressure was the best option. Initial studies of sirens upstream of the combustion chamber were deselected on the basis that they would have to operate choked and this would either significantly reduce the combustor operating pressure or increase the deliver pressure required in the test pipeline upstream of the siren. Therefore, a system where the maximum working pressure within the combustor could be achieved was chosen, which necessitated choking downstream of the combustor and modulation at that plane. In making this choice the engineering of the siren system became more difficult because of the need to cool the siren hardware. The final system used a rotating shaft, however a number of other means of modulating the air across the choked exit of the combustor were considered. One example was the use of valves to inject compressed air immediately upstream of the choking plane was considered. The size and number of valves required for this type of concept made it unsuitable for application on a large-scale rig.

Prior to committing to the pressurised full scale test unit an isothermal small-scale rig was procured and used to develop the concept of the choked exit Siren rig. This rig had a rotating shaft where the profile was changed from square to hexagonal. This design choice was made in order that higher frequencies could be achieved without compromising the quality of the pressure signal for a given motor size. The shaft rotated with an operational pressure ratio total to static of the order 2; i.e. with choked exit. The simulated combustor in the small-scale rig had a circular cross section, with the pressure drop across the combustor being reproduced with an orifice plate. The rig was instrumented with both pressure transducers and hot wire anemometers for recording the unsteady phenomena on the Siren rig in terms of pressure and velocity.

The above mentioned preliminary studies on the isothermal rig led to the design of a multi-sector test unit; see figure 3. The multi-sector rig contains 4 fuel injectors and associated ports. The rig has had its exhaust adapted by adding a transition duct (see figure 4) to accept the Siren unit; a rotating shaft of hexagonal cross-section (see figure 5) at the exit of the transition duct. The shape of the exit is rectilinear and was sized to produce the target flow capacity. The multi-sector geometry had been chosen to avoid any axial or azimuthal acoustic modes in the non-forcing case. However, non acoustic modes, such as entropy waves, are still possible. This larger facility and the mechanism for modulating the flow across an aero-engine combustor / injector system, was aimed at ranking fuel injectors and combustor changes for their propensity to rumble, led to the concept of a rotating hexagonal shaft immersed in the middle of a rectilinear exit profile under sonic conditions as shown in figure 3. The "air-cooled" shaft is capable of operating in hot (1550 K) sonic flow and can vary the choked flow exit area by +/- 15% at frequencies ranging from 10Hz to 800Hz. This rotating mechanism (see also figure 5), known as "the Siren", was attached to the exit of a high-pressure multi-sector combustor casing. The transition duct is also air-cooled, partly by the combustor air circuit and partly by cold rig air, by an external air supply. The cooling passages of the transition duct and those for the shaft are depicted in figures 4 and 6 respectively. A co-axial motor with the aid of a flexible shaft coupling drives the shaft as shown in figure 6.

The motor is operated by a controller that is capable of operating the shaft in "manual" or in "fully automatic" mode for prescribed values of minimum and maximum frequencies, frequency "step" and time duration on a specific frequency.

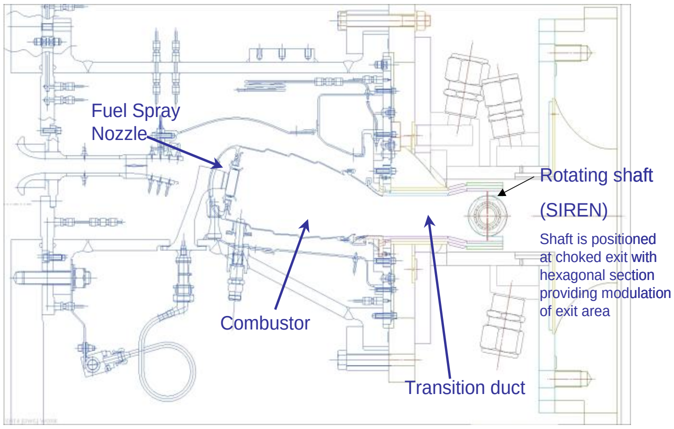

Figure 3 Section of Multi Sector combustion rig with hexagonal rotating shaft (SIREN) at choked exit.

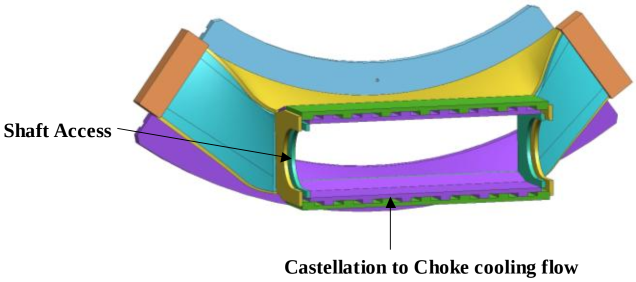

Figure 4 Detail of the transition duct.

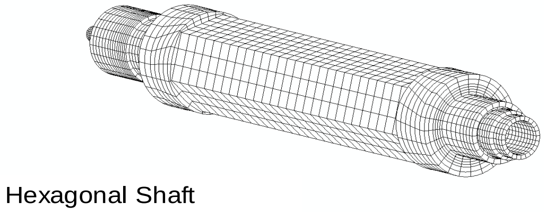

Figure 5 Detail of shaft.

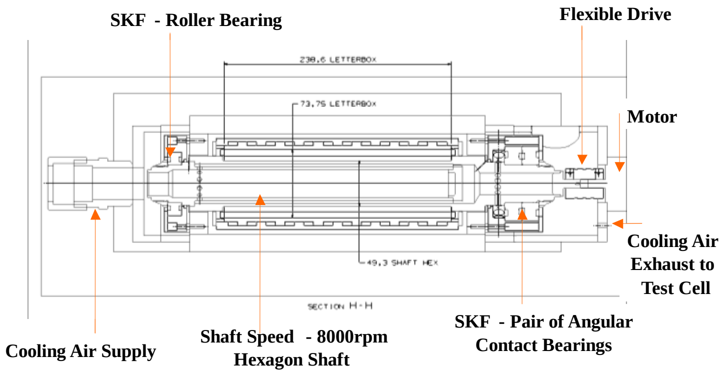

Figure 6 Shaft cooling and bearing arrangement.

The combustor was instrumented with five high temperature dynamic pressure transducers (Vibrometer CP211's) for recording the time varying response of pressure at different locations. These transducers are connected to a data acquisition system (TEAC) and an on-line FFT analyser (OROS). The transducers are positioned appropriately so that the "2 microphone" technique could be used.

4. TEST PROCEDURE AND RESULTS

In order to investigate the "rumble" characteristics of different combustor/injector configurations five different configurations were considered in total; these comprised modifications to the fuel spray nozzle and combustor port holes on the Siren rig, a range of test conditions were selected; see figure 7. For each of these conditions four different air to fuel ratios (AFR) were selected: a typical nominal AFR, two rich and one lean AFR.

In addition, isothermal test cases (i.e. without combustion) were included in the test matrix in order to obtain an insight in the response of the rig itself without the flame perturbation. These isothermal cases have the same inlet conditions as the corresponding conditions with combustion. Thus, the influence of the flame for the different configurations of injector/porting could be studied by comparing these combusting" cases with the isothermal results. Typical results are given in figure 8; this shows the response of the flame, as manifested by the amplitude of the pressure, for different excitation frequencies. This example of the results depict the maximum amplitude recorded for all five different configurations considered for the same test point (i.e. same inlet pressure, inlet temperature and fuel to air ratio) at different frequencies. Evidently, in the range 300Hz to 500Hz, the flame shows higher response for some of the design configurations under consideration. Figure 9 depicts the comparison between the response of the flame and its corresponding isothermal case (i.e. purely the acoustic response of the combustor) for a randomly chosen test point and geometric consideration.

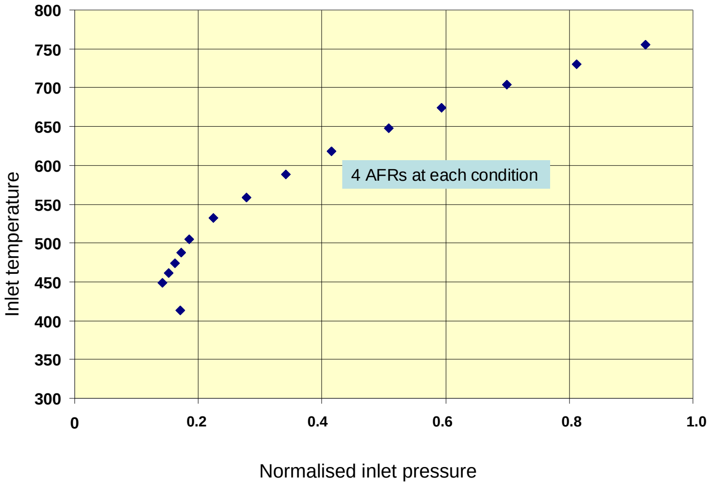

Figure 7 Typical testing conditions.

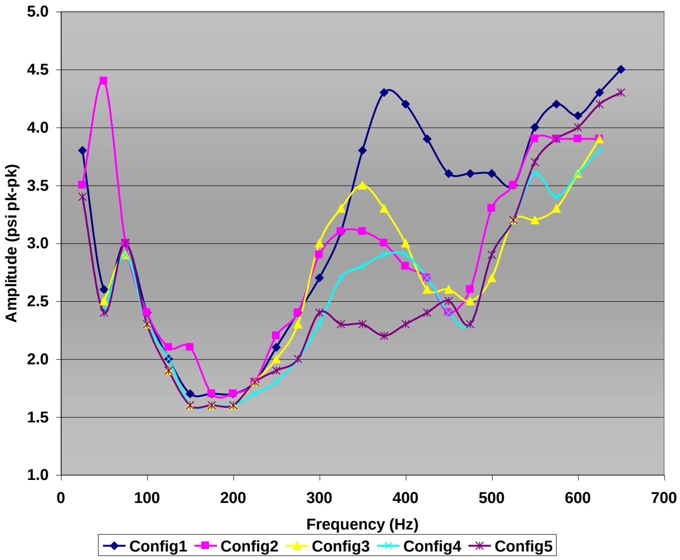

Figure 8 Pressure responses of different build configurations (i.e. maximum amplitude recorded for the five different configurations considered at the same test point for different frequencies).

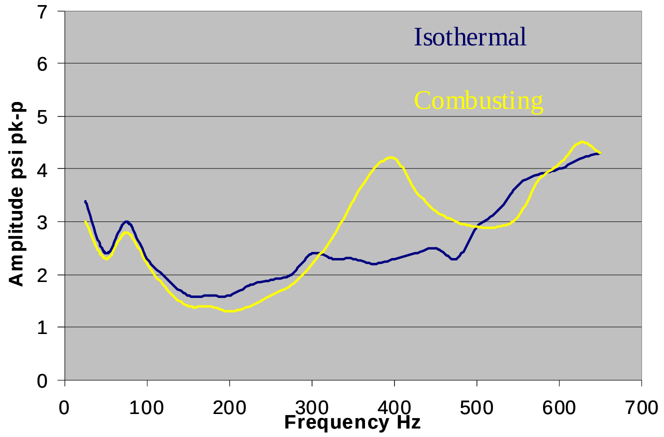

Figure 9 Typical comparisons showing the contribution of the flame to the resulting pressure amplitude for the full range of forcing frequencies.

4.1 Low order thermo-acoustic model of Siren rig

Low order models are used to predict the Eigen modes, in terms of frequencies, growth rates and mode-shapes, of a combustion system. The in-house low order model (LOTAN) calculates for the Eigen modes by solving the linear perturbation in mass, momentum and energy equations by satisfying the acoustic boundary conditions references 17, 18, and 19. The assumption used for linear perturbation theory is given by:

$$f(x,t) = \bar{f}(x) + \left|\hat{f}(x)\right| \exp(i\omega t) \qquad \{1\}$$

Where f is a parameter, which could be pressure, velocity, density, etc.

The acoustic boundary conditions are defined by the diffuser inlet (treated as a hard acoustic boundary condition), although not strictly the case in reality, choked exit (the Siren) and the side walls on the multi-sector combustor. The solid side walls are assumed to be perfectly reflecting surfaces; therefore their reflection coefficient is 1.

It is important to note that the multi-sector combustor size was chosen to avoid all acoustic modes, both axial and azimuthal. However, convective wave, such as entropy waves were still possible. The primary objective of the experiment was to measure the response of the flame to Siren forcing.

The boundary conditions fix the relationship between the unsteady velocity and acoustic pressure at these locations. The aero-thermal boundary conditions are the inlet pressures, temperatures, exit air mass flows and fuel flows. The combustion is modelled within the low order model. The acoustic networks is set up by defining the main acoustic paths through the combustor and cooling annuli, see figure 10 and the cooling flow links between the annuli and combustor. The inlet section is between the inlet diffuser and the inlet to the combustor and annuli.

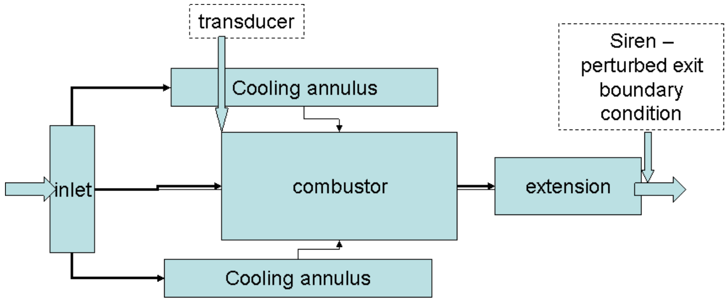

Figure 10 Low order model of Siren rig.

Figure 10 shows the geometry modelled by LOTAN with the essential elements, the locations of the siren and transducers within the network. The Siren is simulated by modulating the choked exit boundary condition by the level of mass flow perturbation (+/-15% of the mean) and provides constant amplitude forcing at all frequencies. The amplitude is scaled from the level of pressure perturbation.

LOTAN uses the simple time delay transfer function, reference 17, which is expresses as:

$$T(\omega) = K \exp(i\omega\tau) \qquad \{2\}$$

$$T(\omega) = \frac{\hat{q}(\omega)/\bar{q}}{\hat{m}(\omega)/\bar{m}} \qquad \{3\}$$

The time delay can be treated by the convective time between the injector and the flame front. This transfer function is essentially a black box which is a function of aerodynamics, mixing, evaporation, fuel type, magnitude of perturbation, frequency, etc.

4.2 Modal response of Sector rig

The 4 sector combustor can be susceptible to both axial and azimuthal Eigen modes. LOTAN is used to calculate both types of modes without a transfer function, therefore assuming no coupling between the heat release rate and acoustic modes. In LOTAN the stability conversion is that positive growth rates are unstable, i.e. the amplitude grows exponentially until the limit cycle pressure amplitude is reached. LOTAN predicts the least stable axial and azimuthal Eigen modes at 858Hz and 562Hz, respectively, see table 1. However, all of the predicted modes are very stable; therefore LOTAN does not predict any self-sustaining thermo-acoustic modes. The corresponding time histories of these axial and azimuthal Eigen modes are shown in figure 11 and figure 12. Figure 11 and figure 12 the history of the axial mode at 852Hz and the azimuthal mode at 576Hz through a single cycle to the acoustic path linking the inlet to the combustor exit. In figure 11 a half wave type mode can be seen in the combustor with a large pressure change across the injector into the inlet section just after to the inlet diffuser. The choked boundary conditions are shown by the large pressure oscillations at the inlet and exit. The pressure oscillations at the inlet are due to the inlet section and the difference in temperature. In figure 12 the azimuthal mode is in the form of a half wave across the combustor sector. Neither the axial or azimuthal Eigen modes were encountered during testing. Table 1 show that there are no predicted self excited modes in the multi-sector combustor within the frequency range of interest (10-800Hz).

axial modes		azimuthal modes	
frequency [Hz]	growth rate [1/s]	frequency [Hz]	growth rate [1/s]
478	-2233	562	-462
539	-2676	749	-1507
858	-1484	1447	-488

Table 1 Predicted Eigen modes.

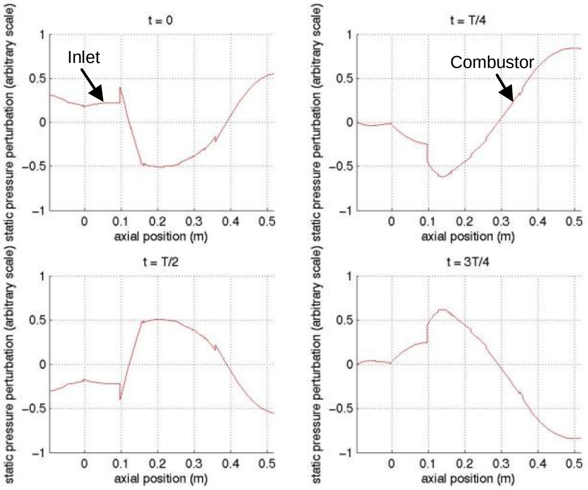

Figure 11 Predicted time history of the stable axial Eigen mode at 858Hz through single cycle.

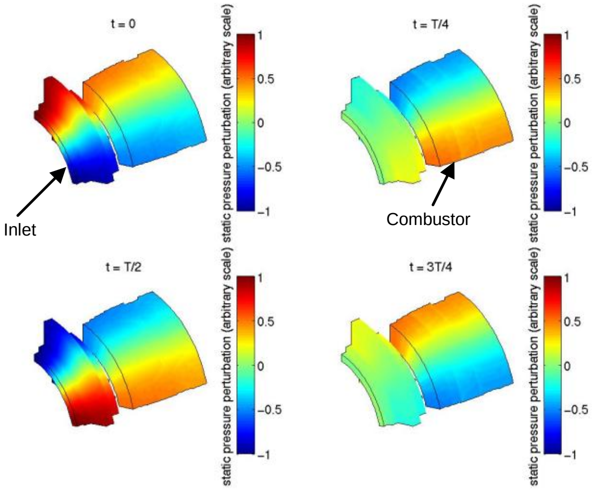

Figure 12 Predicted time history of the stable azimuthal Eigen mode at 567Hz through single cycle.

4.3 Siren linear forcing predictions

Comparison is given between the calculated and measured isothermal responses in figure 13 as a function of forcing frequency between 0 to 700Hz.

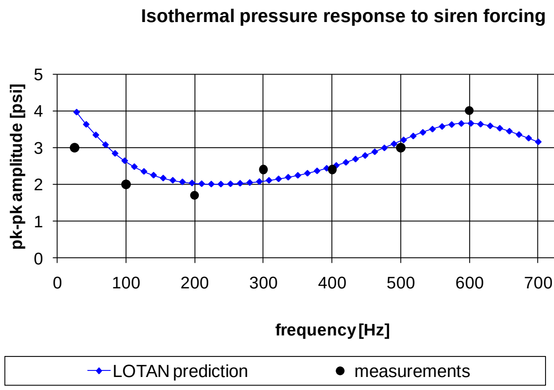

Figure 13 Comparison between measurements and LOTAN predictions at isothermal conditions.

The comparison in figure 13 is fairly good at frequencies above 200Hz. Below 200Hz LOTAN calculates higher amplitude responses compared to the measurements.

A secondary objective of these experiments is to derive a simple flame transfer function directly, from the dynamic pressure measurements. Figure 14 shows a comparison between different LOTAN models and the measured pressure responses to forced excitation. Calculations for a reacting case where no time delay is applied denoted steady combustion case, shows that the calculated dynamic pressure trend is similar to the isothermal case in figure 13. Adding unsteady combustion in form of the transfer function has generated a peak in the pressure response which closely matches the peak frequency and amplitude. This was achieved by tuning the gain and the time delay. In order to do this the time delay is set in terms of the phase between the heat release rate and the unsteady mass flow rate at the injector.

Applying the method described above, Figure 15 shows a comparison between the time delays, in terms of phase, from the Siren rig and measured results from a full annular combustor rig. The spread in the Siren rig results is up to 35% from the average time delay extracted from the Siren rig LOTAN calculations. The extracted time delays are at most 20% shorter than those from the annular combustor tests with the identical acoustic boundary conditions. This is an encouraging result indicating that the transfer functions developed at these low TRL conditions can be extrapolated to full annular rig and engine configurations. Furthermore, the pressure response follows a similar trend to the measurements for frequencies up to 600Hz. This approach provides a means of deriving the simplest of transfer function from representative combustor hardware from only dynamic pressure measurements. This technique will not capture all the possible sources of instability, e.g. aerodynamic and entropy waves.

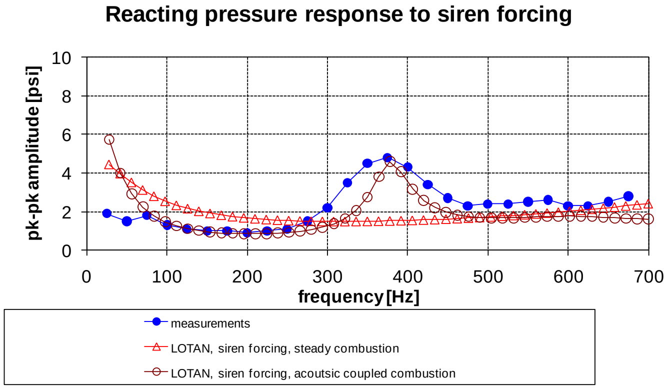

Figure 14 Comparing measured and calculated pressure response of forced excited flame.

LOTAN calculates a higher response in dynamic pressure than observed in the Siren rig tests at frequencies below 100Hz. Furthermore, the forced calculations do not capture the measured bandwidth, which suggests that there is further damping in the reacting flow which is not accounted for in the model. Damping from all the cooling features is included in the form of viscous damping, reference 19.

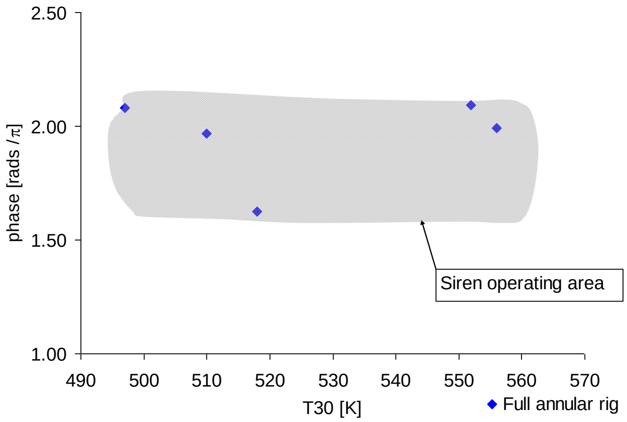

Figure 15 Comparison between time delays, in terms of phase, derived from Siren rig compared to full annular results.

5 DISCUSSIONS

The Siren rig is best described as a tool for assessing the flame response to different frequencies akin to a mechanical vibration test of a part to find the parts natural frequency. The flame is clearly seen to react at frequencies between 300Hz and 500Hz (figure 9) when compared to the isothermal line. The increase in amplitude shows that at these frequencies and at these conditions the flame could react if it can tie in with combustor acoustic frequencies or some other feature (e.g. fuel system vibration) on the engine itself. Data obtained from the Siren rig could be used to map where the combustion flame responds and at what frequency. The measurements would not necessarily read across to an engine in terms of amplitude as in the rig case there is a forced frequency whereas on an engine the natural frequency ties in with the acoustics or some other feature. They are simply used to derive functions expressing the relationship between unsteady heat release rate and unsteady aerodynamics for a range of operating conditions by controlling the modulation of air mass flow rate. These functions are used in conjunction with acoustic linear theory to predict wave modes and growth rates in combustor geometries. Comparison of the datum results (Configuration 1) with full annular rig rumble islands and engine noise measurements showed that the Siren rig could correctly reproduce where noise would occur to within 35%. It was therefore felt that the Siren rig would be a useful ranking tool in terms of potential reductions to rumble or considerations for changing the frequency.

Further configurations were produced that were expected to have some affect on the rumble signature. Configuration 2 and 3 were purposely produced to increase the flame transfer function to try to decouple the frequency from the acoustics (in this case moving to a lower frequency, below any resonant frequency). This rig successfully produced the expected frequency change but did not eliminate the flame response. Configurations 4 and 5 both produced a reduction in rumble amplitude and configuration 5 was selected for further testing at higher TRL. The results of this further higher TRL testing proved that configuration 5 could provide a fix to rumble so it can be stated that the Siren rig delivered its intent to provide a very useful low TRL ranking vehicle.

A couple of other observations on the Siren rig data that can be important and that is (i) it would normally be expected that the pressure amplitude measurement would drop away as the frequency increases but on the rig there is clearly an acoustic resonance of the rig itself that gives higher amplitudes at higher frequencies, (ii) the isothermal line can actually show a higher response at the higher frequencies than when the combustor is lit as in this case the flame can actually be damping rig natural frequencies. The main message is that it remains important to complete isothermal testing and correct the results to enable a true comparison of noisy and quiet flame response.

The siren rig also provided excellent input to modelling tools enabling better modelling of combustors and fuel injectors prior to engine build and testing. The instrumentation present also enabled considerations of any phase relationships within the combustion unit to be understood.

6 CONCLUSIONS

A full-scale Siren rig has been developed and tested at realistic gas turbine combustor conditions. A number of different combustor and fuel injector configurations have been passed over the siren facility. The results as shown in this paper have been useful in determining combustor rumble suppression features. The data gathered from the rig has allowed the transfer functions to be determined and therefore have been used within thermo-acoustic models. The usefulness of the rig to date has been to make back-to-back comparisons of combustor hardware.

LOTAN does not predict any unstable Eigen modes (axial or azimuthal) within the multi-sector rig. Forced isothermal predictions are fairly close to the measurements. In the reacting case a transfer function had to be added to couple the heat release rate. When the transfer function parameters were tailored to the measured peak the forced prediction were fairly good agreement with the measurements.

In summary the Siren rig delivered all the results that were hoped for when the rig was envisaged.

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