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Combustion Oscillations Diagnostics in a Gas Turbine Using an Acoustic Emissions

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Abstract

One of the most important areas of combustion research is the attempt to understand, and control, combustor oscillations, sometimes called “hum” or “noise.” The combustion at very lean mixture produced new problems; “lean” systems have proven to be subject to combustion thermo-acoustic instabilities which could lead to induced pressure oscillations or a “hum”, the humming can increase to howling and cause serious damage to the machines involved unless power output is reduced. In order to begin to understand what humming is, it was necessary to collect and analyze the acoustic signal produced during the humming process occurs in Gas Turbine. In this paper, acoustic signals have been measured in GT combustor of the power plant at Al Rouweas (Bharat Heavy Electricals Limited BHEL, V 94.2 GT power plant) and analyzed during the humming phenomenon. The chosen method for data collection was an acoustic data acquisition system, the acquired acoustic signal was then analyzed with LabVIEW software, the software’s main feature is that capable of defining the acoustic signal (the hum) in many parameters, the most important of which were: power spectrum, auto correlation and the acoustic wave shape produced by the thermo-acoustic instability. The power spectrum gave a concise presentation of the main frequencies which constituted the hum’s acoustic wave pattern, and their relative amplitudes, this was very helpful in determining the acoustic mode of the combustion chamber.

Keywords:Acoustic Signals; Thermo-Acoustic; Combustion Instability; Gas Turbine; Humming.

Abbreviation	Description
NO_x	Nitrogen Oxide
AIC	Active Instability Control
GT	Gas Turbine
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
dB	Decibel
BHEL	Bharat Heavy Electricals Limited
DQA	Data Acquisition
Fig	Figure
et. al	Et alii (and others)
Hz	Hertz

1. Introduction

The objective of this article is to provide the reader with an understanding of the mechanisms and control of combustion driven oscillations, often referred to as “humming.” These instabilities are manifested by oscillations in pressure, rate of heat release and flow rate. Thermo-acoustic oscillations have become a key issue in modern combustion. Although the thermoacoustic phenomenon typically governs, other factors associated with flow dynamics, pressure drop, vortex formation, periodic flame extinction, etc., including fluid-structure interaction effects, may play a role in sustaining the oscillation. Combustion instability is inherently complicated. As a result of this serious problem, it is necessary to find ways of suppressing or reducing the high magnitude of these pressure oscillations. From Rayleigh’s criterion, the thermo-acoustic instability can only occur if the magnitude of the phase between the heat release oscillations and the pressure oscillations at the flame is less than ninety degrees. It should be reiterated that this discussion has primarily concerned itself with the phasing, or timing, aspects of combustion instability initiation. These timing aspects are necessary. The unsteady heat release processes must not only be phased in such a way that they add energy to the acoustic field, but they must be also adding it at a rate that exceeds the rate of damping. Thus, while the associated characteristic times of various combustor processes are important, both the magnitude and phase of the heat release response to pressure perturbations are important issues that determine the stability behaviour of a combustion system. One main gap

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in the diagnostics is the ability to obtain a reliable quantitative measure of unsteady heat-release rate.

Combustion instabilities occur in many practical systems such as power plants. It is well known, the control of NO_x has become extremely important in many combustion systems, to limit the production of NO_x the flame is kept as lean as possible. However, this leads to a more unstable flame, with oscillating heat-release that couples with the pressure acoustics of the chamber. This problem had been revisited earlier on in 1859 by Rayleigh [1]. Rayleigh's criterion has been used in combustion instability studies, which is the coupling between unsteady heat release and acoustic pressure. This criterion states that if the local unsteady heat release q' (z, t), is in-phase with local pressure fluctuation p' (z, t), the pressure wave associated with the fluctuation will be locally amplified. In 1954, Putnam and Dennis [2] put Lord Rayleigh's hypothesis for heat-driven oscillation into a formula, which is known as the Rayleigh integral form:

$$\int_0^T p'(t)q'(t)dt > 0$$

Where p is the pressure, q the heat release, T the time of one period of a cycle and the symbol $'$ denotes the fluctuating quantities. The equation above states that the product of the heat release and the sound pressure fluctuation is integral over a period of oscillation T . If the integral of state is positive, then the oscillation is amplified, if it is negative, damping occurs. In other words, the phase difference or time lag τ between the heat release rate and the pressure oscillation determine whether the instability grows or decays. This leads to the most popular combustion control strategy, a phase shift controller. It senses pressure from the combustion chamber and adds time delay (phase shift) to the signal before the feedback into the acoustic system by a pre-installed loud speaker used to control the dynamic system.

In fact, many industrial and academic institutes have carried out extensive research into combustion instabilities in the last few decades. To suppress or reduce this phenomenon, two methods have been widely used for alleviating or eliminating combustion instabilities, via, passive and active control systems.

A number of studies have been conducted to understand the mechanisms of the combustion instabilities and control strategies of combustion oscillations by using active instability control (AIC). Several experimental studies have been conducted for thermoacoustic interaction in unstable combustors by using conventional active control . It is necessary to have an effective and robust control of combustion. One of several aspects in an active control loop is the sensing technique such as the use of a microphone to pick up the acoustic pressure, and then to an actuator by using feed back close system. Active control has been proposed as a different approach to eliminate combustion oscillations.

The first successful demonstration of active combustion control occurred in 1984 when, using a Rijke tube, a loudspeaker and a microphone as an actuator-sensor pair. Researchers demonstrated that a 40-dB reduction can be achieved in the heat-induced noise. Since then, this technology has grown considerably and has been studied in the context of a number of laboratory-scale (1 to 100 kW), medium-scale (100 to 500 kW), and large-scale rigs (1 MW and above). Control has been achieved in many cases with variable degrees of success. Several experimental results have been reported over the past decade for controlling thermally driven acoustic oscillations using active methods [3-12]. The phase-shift control strategy, which is sometimes referred to as a phase-delay or a time delay strategy, for example Heckl, (1990)[13] successfully used active combustion control extensively from laboratory-scale rigs. Annaswamy et al., (2000)[14] have shown that the loudspeaker dynamics can be modified by the housing used. The housing typically encloses some volume and can act as a Helmholtz resonator making the task of designing a controller more difficult. Richards et al., (1997) [15] made an experimental investigation of a 20 kW atmospheric pressure natural gas combustor; it has been used to study the active control of combustion oscillations. Combustion oscillations arising from fuel/air variations in a premixing fuel nozzle are controlled by periodic injection of fuel in the premixing zone of the fuel nozzle. Specifically, a 300 Hz oscillation with 4.5 kPa *rms* pressure amplitude was reduced by a factor of 0.30 (-10 dB). Control was accomplished using 50 Hz open-loop injections of fourteen percent of the total fuel.

Passive control techniques have been widely used in industrial burners for many years. Their application typically involves modifications to the fuel injector or combustor hardware to eliminate the source of the variation in heat release or to increase the acoustic damping in the system and thereby reduce the amplitude of any pressure oscillations. Typically passive measures are detuning a system by modifying its burners or the acoustics of its combustion chamber, by disturbing the propagation of sound waves via baffles.

Hermann et al., (1999) [16] document further improvements to the control design of a 260-MW heavy-duty gas turbine developed by Siemens AG Power Generation. They used AIC during start-up or part load operations of the hybrid burners. There results showed that, by activating AIC for both dominant frequencies of the second and third harmonics were damped by 20 and 15 dB respectively..

Passive control strategies use devices which are not time-varying in order to eliminate the formation of instabilities. These devices require a thorough understanding or measurement of the system dynamics because they can not dynamically respond to any changes that may occur during operations. Many researchers have avoided passive control specifically for the reason that it can not adapt to changes in the system. Others assert that passive control has failed in the past due to a lack of understanding the fundamental physical phenomena. If a thorough understanding of the system can be attained, then various physical components such as injector geometry, acoustic resonators, liner design, and many other smaller components can be modified or added to remove the instability. Researchers have already experimented with adjusting various components. Gysling et al., (2000) [17] used a Helmholtz resonator side branch, which acts as a notch filter, to reduce the excitation of a predetermined instability frequency. Using these resonators requires a thorough understanding of the combustion system so that the instability frequency can be determined a priori. The resonator's practicality is limited by its inability to adapt to various operating conditions. Schadow et al., (1992) [18] reviewed and studied the combustion instability related to vortex shedding in dump combustors, and their passive control. They showed that the development of heat release, which, when in phase with pressure oscillation, can drive the oscillations as stated by the Rayleigh criterion.

Another passive control technique which has received much attention recently is how the fuel nozzle location affects the potential for instabilities. Many researchers including Steele, (1999)[19]; Straub and Richards, (1998) [20]; Smith and Cannon, (1999) [21] have reported that axial adjustments in the location of the fuel spokes have a positive impact in eliminating thermoacoustic instabilities.

Due to the fact that the use of gas turbines is a very important method of electrical power generation (especially in dry inland regions), and the fact that humming is a real threat to high output power plants, humming is now at the centre of very serious research being carried out by researchers at the top manufacturers of GT power plants across the world. However, this problem is also a local problem, as it occurs at the west mountain GT power -plant (in Al Rouweas Libya), and since this paper is focused at signal processing, it was decided to collect and process humming signals for analysis. The analysis was computer aided via the use of software, and it was decided to use the results of the signal analysis, to determine the combustion mode of GT chamber (the frequency at which humming occurred).

Acoustic emission is inherently linked to flows in which the frequencies of pressure oscillation are within the audible range. It is a known fact that every flow configuration has its unique sound characteristics. However the acoustic emission of a flow is not widely used as a diagnostic source. One of the main drawbacks of acoustic investigation is the lack of spatial resolution. The signals are an integration of the entire space exposed to the sensor. The observation may have significant applications for the monitoring and study of industrial flows. For example, many industrial devices (e.g. gas turbines, jet engines) are difficult to access both optically and electronically. With a proper sound guiding system, the acoustic signals can be collected without much difficulty. Monitoring the engine performance through its acoustic emissions provides a better understanding of the acoustic characteristics of the engine. As well as being aimed at the understanding of the acoustic characteristics of gas turbines, the most important of which being thermo-acoustic instability, this paper is aimed at the study of the methods employed as an attempt to effectively control or reduce instability, passive control is one of -these methods, as well as other significant methods of controlling thermo-acoustic instabilities.

2. Experimental Setup

In this paper the experimental setup and measurement techniques used in this project have been presented. In order to provide accurate measurements of acoustic pressure, and other relevant parameters, a fast sampling system is required. The data acquisition system is based on a fast computer. The Electricity condenser type of microphone has been used to pick up the acoustic signal, its specifications are; Frequency rang 30 ~ 16000 Hz, Polar pattern is Omni directional, and the Sensitivity is -58 ± 3 dB. The microphone is connected to a data acquisition system through a National Instrument DAQ card with a maximum sampling rate of 1.25 Ms/sec and LabVIEW 7 software has been used for the data acquisition, monitoring and analysis. The experimental rig was the combustion chamber of the GT power plant at Al Rouweas The power plant was manufactured by Bharat Heavy Electricals Limited BHEL, and was a V 94.2 GT power plant, Figure1 shows the BHEL power plan. BHEL gas turbines are single-shaft machines of single-casing design. They are suitable for driving generators in base-load and peak-load plants and for mechanical drive applications. They can be used in combined gas-steam cycles and for district heating. They can burn liquid fuels, such as light or heavy fuel oils, or gaseous fuels with different calorific values, such as natural gas or blast-furnace gas. The gas turbine unit consists of the principle components named in Figure 2

The gas turbine uses air as working fluid which is drawn in and compressed by the compressor, Fuel is added and burnt in the combustion chamber, and then hot gas is expanded to atmospheric pressure in the turbine. The exhaust gas leaves the turbine through the exhaust diffuser for discharge into the stack or to the downstream plant components in the case of combined-cycle power plants. The useful output power is available at the compressor-end coupling to drive the generator. After the installation of the necessary signal recording software, the apparatus was assembled as shown in Figure 2, the microphone was placed 2 meters away from the power plant's combustion chamber, samples were taken before, during, and after the humming phenomenon, to provide the necessary data for a complete analysis of the transition from premixed to diffusion flame.

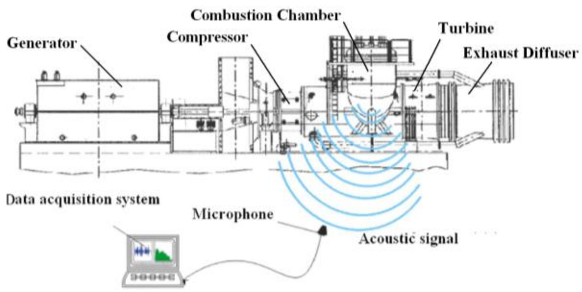

Figure 2.Bharat Heavy Electricals Limited BHEL, (V 94.2 GT power plant) and data acquisition system

3. Results and Discussions

Thermo-acoustic instability is a phenomenon which needs to be analyzed thoroughly when considering its effect on sensitive machines, such as gas turbines. This was taken into account when analyzing the 'humming' phenomenon that occurred at the Al Rouweas power plant, various methods of digital signal analysis were used to provide a clear rendition of the signal in terms of; power spectrum which displays the main dominant frequencies and their relative amplitudes, The correlation of signal (g) values at two instants of time is described by the autocorrelation function ($\Re_g$), which is defined in its most general form by:

Here the time difference, τ, is usually called delay or lag. The autocorrelation function can be determined from a

$$\Re_g(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} g(t) g(t+\tau) dt$$

single sample signal. The function is even and it has its maximum value at τ = 0. With increasing τ, the function usually decreases towards the square of its mean value (the covariance function decreases towards zero). This may take place with damped oscillations. The autocorrelation function approaches zero at great lag values. The idea of autocorrelation function is to compare signal values at different instants of time, a positive $\Re_g$ means that the signal values have often the same sign, and a negative $\Re_g$ means that opposite signs are usually expected. If $\Re_g$ = 0, the relation of the signs is unpredictable. In addition to signs, the absolute values of the signals also contribute to the autocorrelation function. This implies that knowledge of the autocorrelation function, obtained from a measured signal, allows predictions to be made of the signal behaviour. The uncertainty of this prediction grows with time distance. Finally the acoustic wave form which shows the changes that occurs to the waveform during the stages of the transition.

The analysis of acoustic samples have been taken before, during, and after the transitory period (the transitory period is the time at which humming occurs), the actual 'transition' is a change in the type of flame used in the combustion chamber (from the premixed type flame to a diffusion type flame), the apparent cause of thermo-acoustic instability is applying very high loads to the power plant, while operating at a lean air fuel mixture and using a premixed flame, although operating at a lean air fuel mixture while using a premixed flame is both economic and environmentally friendly, as the load increases to very high loads humming occurs, since induced pressure oscillations are a result of humming, the resulting resonance could cause the turbine unit to fail and cause serious damage to the power plant, in order to avoid this, the combustion chamber switches to a diffusion flame type which is less economically and environmentally friendly, this 'switch' has the effect of preventing resonance by altering the frequency of combustion, this type of thermo-acoustic control is deemed as 'passive control', the switch is only temporary, in the sense that the diffusion flame will only be used until the load returns to its normal state. The whole process will be referred to as the ''transition'', and the results of its analysis are as follows.

The acoustic signal that was recorded starts from about 2 minutes before the actual transition and continues to about 2 minutes after the transition, The sampling rate is 44100 s/sec and number of samples is 20000). a sample taken at the time before transition was analyzed, the results are as shown in figure 3, the power spectrum a shows that the dominant frequency is at approximately 50 Hz which is the frequency of the electricity produced by the power plant, the auto correlation shows that the signal is repetitive (is not merely noise), and the wave form also shows that it is a repetitive acoustic signal.

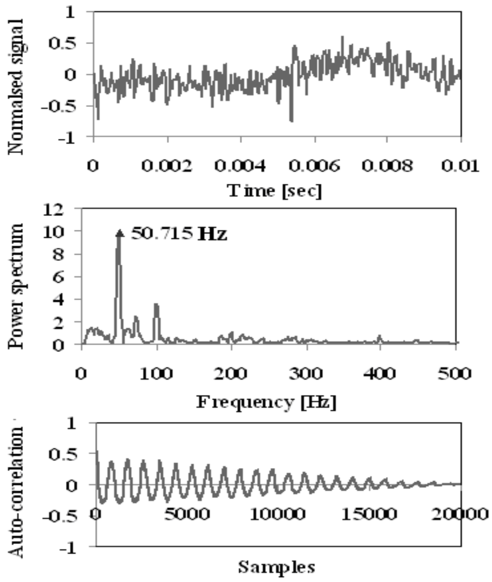

Figure 3.Power spectrum, Wave form, and Auto-correlation of sample taken before transition (premixed flame in use)

Another sample taken at the actual time of transition shows the changes that occur as resonance takes place, the power spectrum Figure 4 shows that the previous dominant frequency of 50 Hz has been dwarfed by a new dominant frequency of 72.765 Hz, which is the frequency at which resonance occurred i.e. the frequency at which the induced pressure oscillations matched the natural frequency of the combustion chamber. The transitory period is slightly noisier, the power spectrum also shows that the transitory period is slightly noisier, the auto-correlation Figure 4 shows an increase in the signals repetitiveness (correlation), this is due to the amplitude increase during the transitory period (from 9.852 volt (before transition) to 28.46 volt (during transition)) the increased amplitude of the dominant frequency means that the auto-correlation will be less affected by noise. The wave form Figure 4 also shows an increase in frequency and is slightly distorted by the increased noise level.

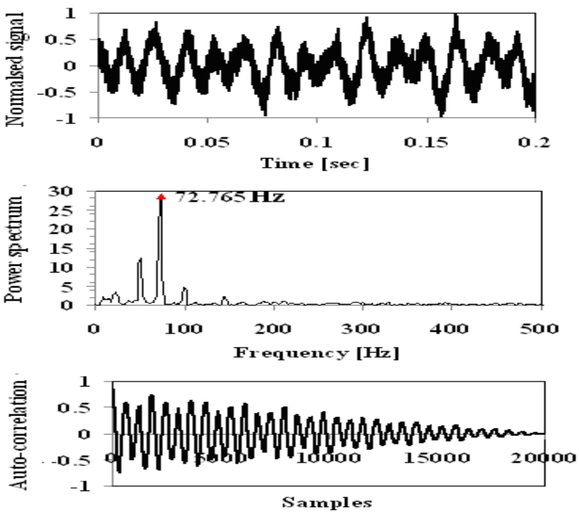

Figure 4.Power spectrum, wave form, and Auto correlation of sample taken at transition

Measurements taken using a sound pressure level meter confirm the increase in overall noise level; the measurements show a substantial increase in sound pressure level (from 98dB before transition to 123dB during transition).

The final sample was taken after the transition; the power spectrum Figure 5 shows that the dominant frequency has returned to the previous 50 Hz and that the noise level has decreased from what it was during the transition, the auto-correlation; Figure 5 shows a decrease in correlation due to the decrease in the dominant frequency's amplitude.

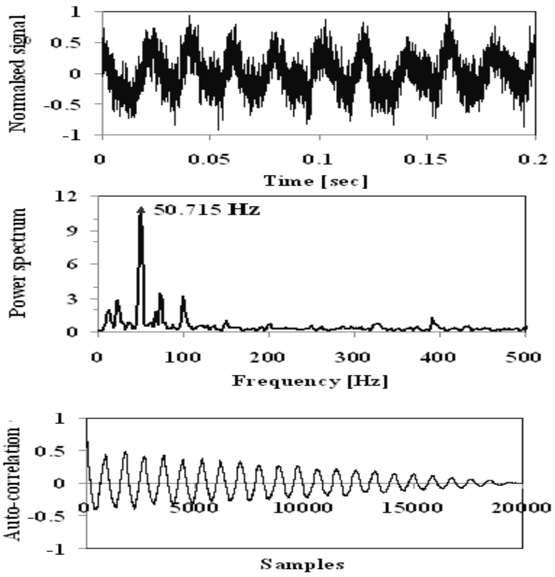

Figure 5.Power spectrum wave form, and Auto-correlation of sample taken after transition.

To compare between the general acoustic behaviour of premixed and diffusion flame, the power spectrum of the sample taken at the time when premixed flame was used, was superimposed on the power spectrum of the sample taken when diffusion flame was used. as shown in Figure 6.

From Figure 6 it is apparent that the power spectrum of the signal sample taken after humming has higher peaks, what this means is that the signal is more pure, or contains less noise than the signal taken before humming. From this it can be deduced that combustion at lean premixed conditions is noisier and less stable than combustion with a diffusion flame type.

Figure 6.Power spectra of samples taken after, before and at transition.

4. Conclusions

After the analysis of the results, a few conclusions were reached, the most important of which is the great effect thermo-acoustic instabilities have, on the performance and expected life span of turbo-machinery, this effect was encountered during the form of the humming phenomenon that occurred at the Al Rouweas GT power plant, the problems arising from the humming phenomenon that occurred when the combustion frequency matched the natural frequency of the power plant (experimentally found to be 72.765 Hz), were addressed via the application of passive control, which involved the switch from premixed to diffusion flame type.

Engineers at the power plant have found a solution that helped reduce the occurrence of the humming problem, since two of the fuel pre-heaters were offline the fuel's inlet temperature was lower than the design temperature of 20 ^{o}C, the offline fuel pre-heaters were repaired and reinstated, this increased the inlet fuel temperature back to 20 ^{o}C, the increased inlet fuel temperature caused a dramatic change in the repetitiveness of the humming phenomenon, from an almost daily occurrence, to a near weekly occurrence. The cause of this change is unknown and should be the centre of future research.

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