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AS6320 Acoustic Instabilities in Aerospace Propulsion
Assignment 1 : Thermoacoustic instability in SGT-750 Combustion system

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An experimental or computational study of combustion instability is an area of importance to gas turbine, has demand in the fields of aviation and power generation, and this topic has recently become more prominent.

1 Introduction

Thermoacoustic instability is the interaction process between a combustion process and acoustic field which leads to self-sustained oscillations. If not kept under acceptable limits, the oscillations may grow and cause wear and structural damage. This study describes the mechanisms behind this instability.

Since combustion is a driver for the instabilities, we will review few combustion concepts-

1.1 What is combustion?

Combustion is a chemical process in which substance reacts rapidly with oxygen and gives off heat. The substance is fuel and oxygen is the oxidizer. The fuel for gas turbine is hydrocarbon. The chemical reaction when methane is burnt in air is -

$CH_4 + 2\,O_2 \longrightarrow CO_2 + 2\,H_2O + \text{Heat}$

The heat release within a combustion process appears as a flame which propagates through the unburned mixture with a certain burning velocity. The flame, a thin layer with rapid chemical changes and a steep temperature gradient, is the interface that divides the burned mixture from the unburned mixture in a combustion process.

Flame can be categorized as premixed or non-premixed flames or also by laminar or turbulent depending on the initial state of reactants.

Premixed flames mix fuel and oxidizer before entering the flame zone, while non-premixed flames mix by diffusion within the flame zone. Premixed flames are more sensitive to disturbances and stability issues due to steep concentration gradients in the intermediate mixing region. In contrast, perfectly premixed mixtures lack such gradients, making the flame location highly sensitive to disturbances.

The **equivalence ratio** is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. An equivalence ratio higher than 1 means there is an excess of fuel to the available amount of oxidizer, this is called fuel-rich and will give unburnt fuel as a rest product. If the equivalence ratio is less than 1 there is an excess of air to the amount of fuel to be burnt. This condition is called fuel-lean.

For a combustion process that takes place adiabatically with no shaft work, the temperature of the products is referred to as the **adiabatic flame temperature**. This is the maximum temperature that can be achieved for given reactants. Heat transfer, incomplete combustion, and dissociation all result in lower temperature. The maximum adiabatic flame temperature for a given fuel and oxidizer combination occurs with a stoichiometric mixture (correct proportions such that all fuel and all oxidizer are consumed). The amount of excess air can be tailored as part of the design to control the adiabatic flame temperature.

1.2 Combustion instabilities

Combustion instabilities can be divided in two categories, *Combustion noise* and *Thermoacoustic instabilities*.
The sound is generated by unsteadiness in the rate of expansion by combustion of gas. The turbulence creates flow variations which causes combustion and results in **combustion noise**.

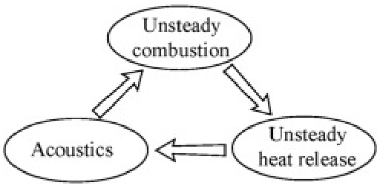

Figure 1: Feedback loop between unsteady flow and acoustics

Thermoacoustic instabilities are excited by the feedback loop between the unsteady combustion and natural acoustic mode of combustors, as shown in the figure. The heat transfer in the combustors is enhanced spontaneously when the instabilities occur. Therefore, the components in the combustors are more prone to be melted, and the systems then lose efficiency or become disabled.
Acoustic waves can be generated in two ways in combustion processes: directly through volume fluctuations due to unsteady heat release, and indirectly through temperature fluctuations called entropy waves. Entropy waves are not associated with acoustic fluctuations of pressure and velocity, and do not produce noise. However, when an entropy wave is accelerated, acoustic waves are indirectly generated.

1.3 Rayleigh's criterion

The Rayleigh Criterion is the standard tool to predict combustion instabilities both in experimental and numerical studies. It is a criterion for *assessing the stability* of a combustor. Energy transfer to the acoustic field depends on the phase difference between the unsteady pressure and heat release. Maximum energy input happens when they are perfectly in phase. On the other hand energy is removed if they are out of phase.
For real systems, some portion of the acoustic energy propagates out through the boundaries or gets dissipated by friction and viscous effects.

$$\int_V \int_T p'(x,t)q'(x,t)dtdV > 0 \tag{1}$$

Here p and q stand for pressure and heat release fluctuations respectively and V is the flow domain. The equation is integrated over a period to characterise the stability of the system at a given frequency.

1.4 The Rijke Tube

Apparatus
It is a open-ended vertical tube with a confined heat filament in it's lower half. And a net flow of gas through the tube is generated due to the natural convection, which is essential in producing self-sustained oscillations.

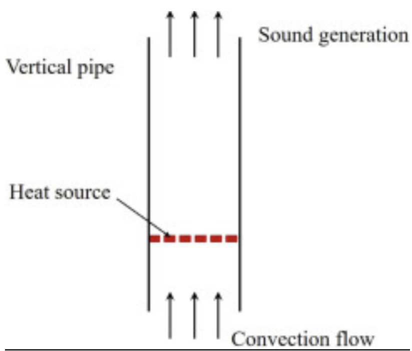

Figure 2: The Rijke tube

How is works?
The hot filament causes the air to heat up. Hot air rises, maintaining a convection current in tube. When a sound wave of right pitch enters the tube, it increases the pressure in the tube. Air entering from below of the tube slows down as it pushes against this pressure. So the air receives less heat and average temperature of tube cools a little. Cold air contracts and lowers the

pressure sucking air faster. This causes more heating, rise in temperature, causing air to expand, repeats the cycle again. All this happens 100 times a second, making an eerie sound.
The phenomenon can be understood using Rayleigh's criterion. The first mode of an open-ended tube has pressure nodes at the ends and a velocity node in the middle. Placing the heat source in the lower half of the tube will render a positive value of the Rayleigh's integral and the acoustic oscillations will be sustained and amplified. In contrary, placing the heat source in the upper part of the tube, the Rayleigh's integral will give a negative value and the acoustic oscillations will instead be attenuated.

2 Setup

2.1 Gas Turbines

Gas turbine engines work according to the Brayton cycle and can be divided in three main parts, compressor, combustor and turbine. Compressor compresses the air and sends to the Combustor where fuel is introduced and the mixture is burnt. The turbine drives the compressor as well as combustion gases are expanded to give a net power output to drive a generator or pump. There are 2 types of gas turbine combustors - can and annular type. In a can combustion system, each burner has its own combustion chamber. It is easier for service and maintenance. While in annular, all burners go into one large combustion system.

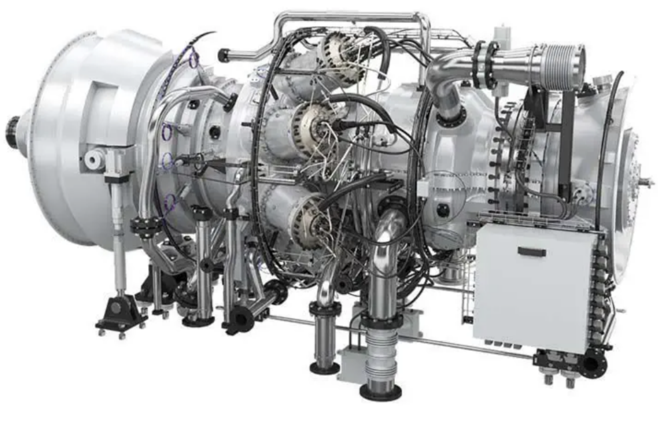

Figure 3: SGT-750 Gas Turbine

2.2 The SGT-750

The SGT-750 has the highest power and efficiency and is proven to be one of the most eco-friendly turbines in the world. The turbine and compressor are disconnected from each other which makes it suitable for mechanical drive applications.

3 Discussion

3.1 Driving mechanisms for thermoacoustic instabilities in gas turbines

3.1.1 Equivalence ratio fluctuations

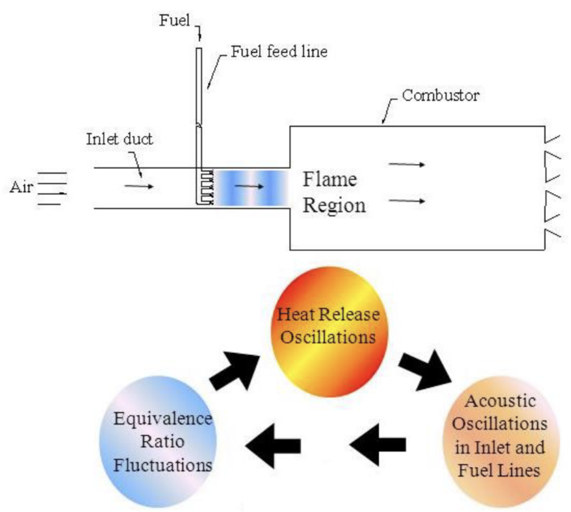

Figure 4: Mechanism for combustion instability due to equivalence ratio fluctuations

In practical situation, any acoustic oscillation present in a premixed combustion system causes variation in mass flux of air and fuel supply which causes equivalence ratio fluctuations. This is in consideration to time-lag theory which describes the effect of phase difference in the combustor.
This equivalence ratio fluctuation is convected downstream to the flame, inducing flame heat release fluctuation. This creates a *convective time lag.* In addition to this, there is another time lag, known as *chemical time lag* which is the time for the air-fuel mixture to burn completely and generate

the combustion products. Thus the total time lag is the transport time for oscillations from the point where fuel and air and injected to the flame front. If heat release oscillation induced by equivalence ratio fluctuation is in phase with the pressure oscillation at the flame front, it will amplify the oscillation. If it is out of phase, oscillations will decay.
The equivalence ratio can be controlled to oscillate between two limits, to avoid thermoacoustic instabilities.

3.1.2 Coupling acoustic-fuel feedline

Feed-system coupling is a process where pressure fluctuations in the combustor and fuel-delivery system cause a fluctuating fuel concentration, which is then connected to the flame front, resulting in a fluctuating rate of heat release. In-phase fuel fluctuation amplifies oscillations, while out-of-phase fluctuation dampens them. This process is crucial in maintaining efficient combustion.

3.1.3 Flame area Variation

The instability of the laminar flame front can be caused by changes in the flame structure due to the difference in the diffusion coefficients of the components of the combustible mixture, leading to a partial change in the composition of the mixture (enrichment of the mixture with a faster diffusing component) immediately before the flame front.

- Acoustic velocity oscillations inside a combustor will affect the flame area.
- Thermal losses when flame impinges on cold wall can affect the chemical reaction and cause the flame area to vary.
- Interaction between flames can cause the flame area to vary.
- Flame-vortex interaction which refers to periodic separations created by e.g.flame holders or other obstacles in the flow path. The vorticity generated convects with the flow and stretches the flame

3.2 Measures to improve stability

3.2.1 Improving the shape : Changing combustor length

We can change the property of the acoustic system by changing the combustor cans length. The change in length will cause a change in mode shape and heat released may be located in a region with low pressure amplitude for that particular mode. Hence less acoustic energy will be transferred to the field according to rayleigh criteria. The risk can be that the mode which was stable becomes unstable.
A study was performed where combustor length was increased and decreased by 100 mm. The first mode showed minimal differences due to small length changes compared to wavelength. However, the model suggests that length should not be increased as it predicts a slight growth rate increase.

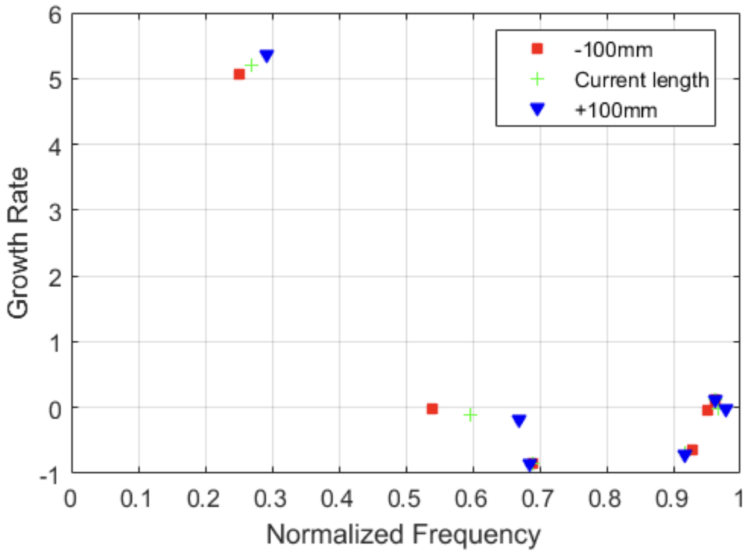

Figure 5: Stability plot

3.2.2 C-stage

Fuel injection upstream the burner allows for a better mixing of the fuel and oxidizer which is good in order to lower emissions. This is called c-stage in SGT-750 combustion system. On the other hand, the amount of fuel introduced must be low enough to not give a combustible mixture for safety reasons.

3.2.3 Using a Helmholtz resonator

Helmholtz resonator (HR) is a widely used acoustic damper that can effectively dissipate acoustic waves in combustion systems. It consists of a cavity volume connected to a combustor via a short neck. At resonance, the fluid mass in the neck oscillates, causing gas/fluid in the cavity volume to be compressed and expanded. This periodic motion results in thermo-viscous and vortex shedding losses, which are the main damping mechanisms of the HR. The HR damping effect is maximized when the oscillating velocity is maximized, which can be achieved by tuning the resonator to match the frequency of combustion-excited oscillations.

Figure 6: A brass spherical Helmholtz resonator based on its original design

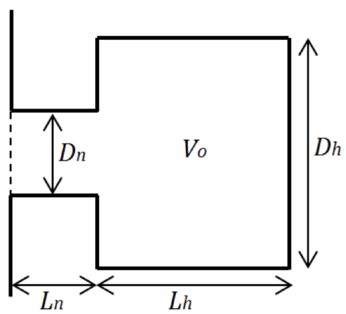

Figure 7: Schematic of Helmholtz resonator

The helmholtz frequency is determined by the geometric dimensions of the resonator as -

$$f_H = \frac{c}{2\pi}\sqrt{\frac{A_n}{V_0 L_n}} \tag{2}$$

where A_n is the neck cross section area, L_n is the length of the neck and V_0 is the volume of the chamber.

4 Summary

In this work, I started with basics of combustion and combustion instabilities. Thermoacoustic instabilities are excited by a feedback between unsteady combustion and natural acoustic mode of combustors. The Rayleigh's criterion is a tool for assessing the stability of the combustor. his criterion states that the acoustic energy increases when the heat-release rate is sufficiently in phase with the acoustic pressure. Sound production in the Rijke tube is a classic example of a thermoacoustic phenomenon. The Rijke tube is simply a cylindrical tube with both ends open and a heat source placed inside it. The tube is positioned vertically on a stand and the heat source is introduced from below into the tube. For certain ranges of position of the heat source within the tube, the Rijke tube emits a loud sound.

I have discussed the thermoacoustic instabilities in the SGT-750 combustion system. Equivalence ratio fluctuations, coupling acoustic-fuel feed line, flame area variation are some driving mechanisms for thermoacoustic instabilities. Changing the combustor length, including Helmholtz resonators and c-stage are some methods to improve stability. Equivalence ratio fluctuations in premixed engines can cause combustion instabilities due to acoustic perturbations in the premixing section. These fluctuations affect the air and fuel supply, leading to periodic oscillations and unsteady heat release. Fuel feed line-acoustic coupling is a type of equivalence ratio fluctuation where pressure drop over non-chocked nozzles modulates the fuel injection rate. Origins can be on the fuel line or in the combustor. The flame generates acoustic waves, leading to pressure fluctuations over fuel nozzles upstream, causing periodic fuel injection and convection to the flame front. The heat release at the flame front is proportional to the flame surface area. Several reasons and mechanisms are discussed which vary the flame area in the gas turbine combustor which leads to fluctuating heat release.

Finally a few mechanisms to improve thermoacoustic stability were discussed. To enhance stability, alter the length of combustor cans by altering the acoustic properties of the system. This can result in lower pressure amplitude for heat release, reducing acoustic energy transfer. Helmholtz resonators can damp a combustion instability in combustor but their small operation window around f_H necessitates tuning for each frequency of interest. The c-stage allows for further distribution and careful optimization of convective time lags.

Overall, studying thermoacoustic instability in engines and combustors is necessary to improve efficiency, ensure safety, reduce emissions, enhance durability, and advance the development of next-generation combustion technologies.

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