Chapter 1-Introduction

1.1- Origins of Thermoacoustic Instabilities

In the last decade environmental restrictions have been implemented to reduce the emissions from gas turbines. A primary focus has been to reduce the nitrogen oxides (NOx) emissions below 25 ppm. NOx forms in high temperature environments where there is enough energy to overcome NOx's high activation energy. Many gas turbine manufactures have changed their combustion process in order to reduce the flame temperature and thus reduce the high energy environment conducive to forming NOx. This was accomplished by using a lean pre-mixed flame rather than the standard diffusion type flame. A diffusion flame burns where air and fuel meet at stoichiometric proportions, which is defined as an equivalence ratio of 1 ($\phi \sim 1$). This produces the highest possible flame temperature. The lean pre-mixed flame involves pre-mixing the air and fuel in proportions which make the mixture fuel lean ($\phi < 1$), thus lowering the flame temperature and not allowing the high energy environment needed for NOx formation.

Pre-mixed flames reduced the NOx emissions to acceptable levels, but in the process generated large pressure oscillations inside the combustion liner for certain operating conditions. The pressure oscillations were found to generally occur at frequencies associated with the natural acoustic resonances of the combustion chamber. These instabilities were designated as thermoacoustic (TA) instabilities since it became apparent that the characteristics of a pre-mixed flame excited the natural acoustic modes of the combustion chamber. Because the fuel/oxidizer mixture is pre-mixed, the flame is much shorter, creating a zone of intense localized heat release which has the ability to excite certain acoustic frequencies. A self-excited loop is created in which the oscillating pressure field pulsates the incoming fuel/air mixture to the flame, therefore causing the heat release from the flame to oscillate, which creates even larger amplitude oscillations in the pressure field, etc…. These pressure oscillations can generate high-cycle fatigue on the combustion liner which reduces the gas turbine's longevity and reliability. Also, the unsteady heat release makes the temperature profile entering the turbine section uncontrollable, thus reducing the turbine's efficiency and the life span of the turbine blades. Thus, research has been ongoing to reduce or control the generation of large amplitude pressure oscillations in gas turbine combustors. Collaboration between industry, government, and university resources has been important in the process of understanding the physical nature of the problem, and developing solutions.

1.2-Motivations and Objectives

1.2.1-Motivations

Most of the work involved with eliminating TA instabilities has been focused on developing both passive and active control strategies. In general, researchers have concluded that passive techniques are not adequate because they cannot adapt to changing operating conditions. Active techniques have had some success, but often suffer from a lack of detailed acoustic and heat release models. Modeling the physical phenomena associated with TA instabilities has proved very difficult due to the complexity of the system and the highly non-linear elements associated with certain components. Many of the models developed to date involve only specific components of the entire system. Controls, combustion, and acoustics are vastly different research areas, therefore it has been difficult for researchers specialized in one field to generate an all encompassing system model and control scheme. Two major issues must be addressed in order to solve this problem. First, detailed analytical models must be created to facilitate better control schemes, and increase the physical understanding of the problem. Secondly, there must be a collaborative effort among researchers from each discipline so that any model developed incorporates the expertise of each group.

1.2.2-Objectives

The work to follow will describe how a system-based model, incorporating all of the major dynamic components, was created and used to perform a stability analysis on a single injector test rig operated by Solar Turbines Incorporated. Figure 1.1 shows a picture of the test rig. This rig is used mostly for injector design studies, but it provides a relatively simple platform to develop a system-based model to predict instability frequencies. Even though the test rig is simpler than an actual gas turbine combustor, it still retains many of the same components and operating conditions seen in the actual combustor. These include comparable operating temperatures and pressures, similar fuel air mixing schemes, and swirled inlet air. The modeling process can be thought of as a proof of concept. If the process shows that it has the ability to predict instabilities, then the methodology developed during this exercise can be applied to more complicated systems such as a full scale gas turbine engine.

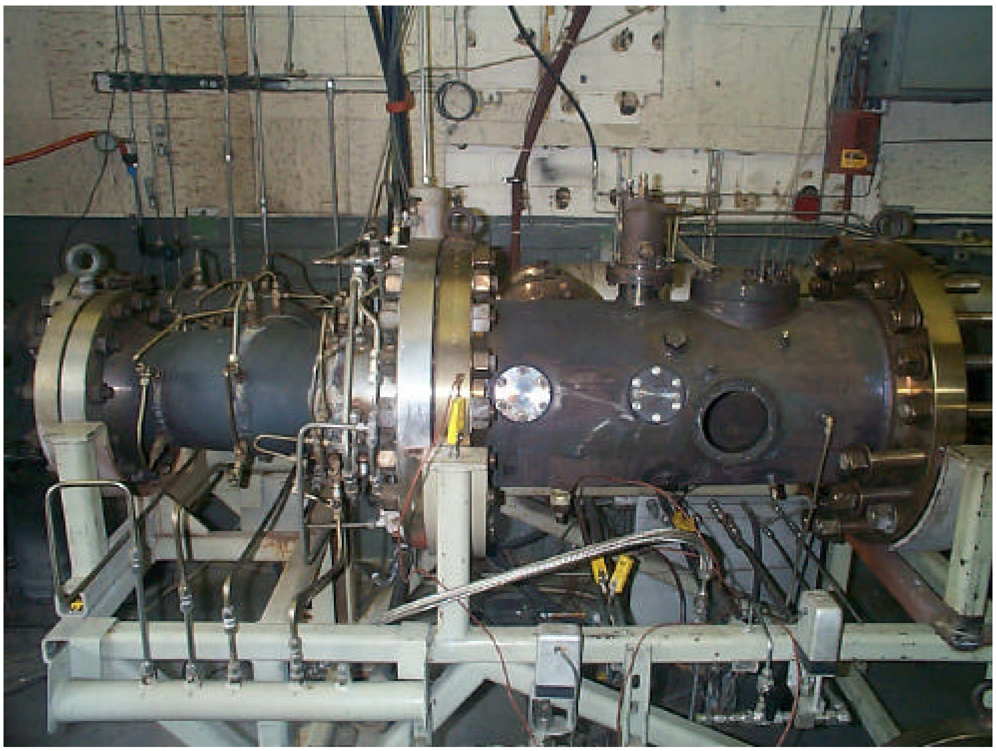

Figure 1.1-Single injector test rig used to create a model for predicting thermoacoustic instabilities.

Figure 1.2 represents a block diagram created to model the thermoacoustic instability process in combustors such as the one shown in Figure 1.1. Dynamic input/output relationships will be derived for the acoustics and combustion. These blocks will be connected by the appropriate scaling and a time delay which represents the delay time between when the fuel is injected and when it burns at the flame front. Below is a list of reasons and desired results for undertaking this modeling process:

-Attempt to validate the individual components of the system to make sure the model reflects physical reality.

-Use the system model to perform a stability analysis to determine the frequency bands where instabilities will exist. (Note: A linear stability analysis will provide instability frequencies, but it will not provide unstable limit cycle amplitudes due to the non-linear affects of the system.)

-The time delay element will provide designers with a simple control parameter which can be used to move the system out of potential instability frequency bands.

-The process of creating a system-based model will result in the development of a design methodology which will be applicable to any gas turbine combustor system.

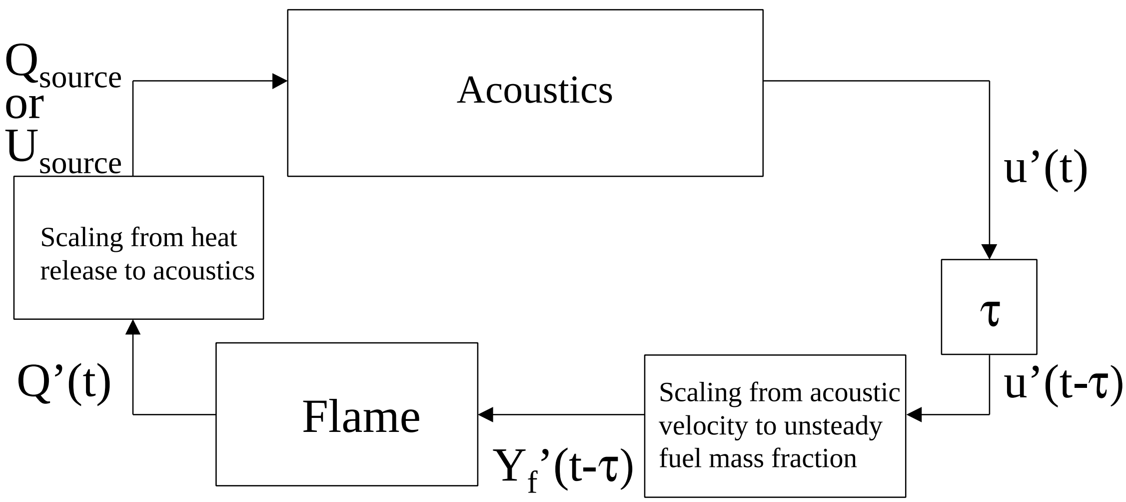

Figure 1.2-Block diagram of self-excited combustion system capable of generating thermoacoustic instabilities.

Passive control of the self-excited system (Figure 1.2) relies on the adjustment of the time delay element to change the phase of the system so as to favor stable operations. Through the use of detailed models and adjustments to the time delay element, stability can be ensured for large frequency bands during the design phase. These bands will allow for many stable operating conditions, although a simple time delay element probably will not generate stability over the entire range of operating conditions.

1.3-Summary of Research Results

In general, the linear stability model was able to predict instability frequencies for some of the operating conditions of the Solar test rig, but failed to predict instability for other operating conditions. The inconsistent nature of the results indicate that the system model fails to capture all of the relevant dynamics. However, it will be shown that the time delay can be used as a control parameter, and its influence in the model predictions is striking. The problems associated with the system model resulted primarily from a lack of detailed component models, but the results indicate that the design methodology is valid. Many of the models such as the flame, the hot acoustics, and the time delay lack validation. Obtaining detailed models is very difficult since many of the unknown parameters and components are very hard to measure experimentally. Future work will involve developing validation techniques so that the component models can be refined. Conclusions about each component of the model are listed below:

Acoustics:

-The acoustics provide most of the dynamic character of the overall system. Therefore, high and low gain areas in the acoustics will produce corresponding high and low gain areas in the system model.

-Room temperature experimental data was used to validate the acoustic model producing very good agreement. Future work will involve developing experiments to measure the acoustics at operating temperature so that the high temperature model can be validated.

Heat Release:

-The flame was modeled as an unsteady well-stirred reactor with single-step kinetics. The model seems to under-predict the value of the unsteady heat release. At this time, this inaccuracy is thought to be attributed to some of the simplifying assumptions made in the well-stirred reactor (WSR) heat release model. Ongoing work is being conducted to measure unsteady heat release in pre-mixed flames using heat flux gauges and OH* measurements. This work will be followed by similar experiments on more realistic gas turbine combustors.

-The WSR heat release model indicates that the flame adds gain to the system and acts as a low-pass filter. The low-pass nature reduces the gain of the system enough to eliminate the potential for instabilities at higher frequencies.

Time Delay:

-By definition, the time delay adds additional phase to the system, thus it has the ability to change the value of the instability frequency. Because it can change the instability frequency, the time delay may be useful as a control parameter in the combustor design phase to create frequency bands that will not produce instabilities.

-The time delay is difficult to know precisely since the convective distance from the fuel injection location to the point of heat release is not clearly defined. The primary uncertainty is associated with determining the precise spatial volume where the heat release occurs. Measurement techniques must be developed in order to create a systematic way of determining the actual convective distance from the nozzle to the location of peak heat release.

1.4-Thesis Outline

The remainder of this document will describe the process used to obtain the stability analysis results. Chapter 2 provides a history of the work done in this area by other researchers. The literature review presents information on what others have done to control this problem and motivate the work presented here. The next two chapters present the acoustic modeling needed for the single injector test rig. Chapter 3 provides background acoustic information and models for simple systems used to validate the modeling procedure for specific components of the test rig. Chapter 4 presents the process used to develop an acoustic model for the entire single injector test rig. Much of the effort in Chapter 4 focuses on correcting the analytical models so that they match the experimental data, and also on identifying which geometric components of the test rig dominate the acoustic response of the system. Chapter 5 presents the development of a heat release model proposed by Fannin [5]. Conservation equations are derived for an unsteady well-stirred reactor using simple one-step Arrehenius kinetics. These equations are linearized and solved for small deviations from an equilibrium condition. The last chapter shows the steps used in assembling the entire system model, explains the stability analysis procedure, compares the model predictions to experimental instability data, provides conclusions, and presents issues for future work.