Chapter 2-Literature Review

Chapter 2 presents previous research conducted in the area of thermoacoustic instabilities. Much of the work has been prompted by industry's need to understand and control this problem in order to produce less polluting gas turbine engines.

2.1- Origins of Combustion Driven Instabilities

Regulations on the emissions from gas turbines has prompted manufactures to design less polluting engines. Efforts have focused on the reduction of nitrogen oxide or NOx emissions. Sood [28] provides a general discussion on the chemistry involved in the creation of NOx and other emissions in gas turbine combustors. Richards, et al. [26] discuss numerous techniques that have been used to reduce NOx emissions. These include exhaust stream cleanup which uses ammonia to convert NOx to molecular nitrogen, direct water injection into the combustion liner to lower the exhaust temperature, lean-premixed combustion which lowers the combustion temperature, and catalytic combustion which allows for combustion below the flammability limit. The use of ammonia and water has proven difficult and expensive to implement due to the additional equipment needed. Catalytic combustion appears to be viable in the future, but currently only experimental catalytic systems are being used. Therefore, gas turbine manufactures have turned to lean-premixed combustion in order to reduce their NOx emissions. Lean-premixed combustion reduces NOx emissions by lowering the flame temperature so that there is not enough energy to overcome the high activation energy needed to form nitrogen oxides. When lean-premixed combustion was implemented gas turbine manufactures were able to reduce their NOx emissions below 25 ppm., but in the process they also generated instabilities in the combustion chamber. These instabilities produce large amplitude pressure oscillations which lead to an uncontrollable temperature profile at the turbine inlet and fatigue of the combustion liner.

Two types of instabilities are known to exist in combustion chambers. Intrinsic instabilities are due to the combustion process itself, while system instabilities involve a coupling between the combustion system and the combustion process. Kailasanath and Gutmark [13] and McManus et al. [19] discuss the characteristics and consequences of each type of instability. Intrinsic flame instabilities include Landau-Darieus instabilities caused from density variations between products and reactants. Differences in species diffusion rates cause thermodiffusive instabilities, and reaction rate imbalances between the numerous reacting species can create chemical-kinetic instabilities. System instabilities can be generated from fluid-dynamic instabilities such as vortex shedding from the inlet of a dump combustor or large-scale coherent structures generated by shear flows (i.e. boundary layers). Another system instability, known as a thermoacoustic (TA) instability, involves the coupling of acoustic waves and the unsteady heat release from the flame.

Since gas turbine manufactures observe large amplitude pressure oscillations it is obvious that the acoustics of the system are being driven unstable, but the driving force behind the instability is not obvious. The critical issue is whether the acoustics are being driven unstable by unsteady heat release from a fluid mechanic instability, or whether there is a feedback mechanism between the acoustics and heat release from the flame. Both mechanisms are being investigated and results supporting fluid mechanic coupling are reported by Paschereit et al. [23] and Gutmark et al. [7], while results supporting a heat release feedback mechanism are reported in Culick et al. [3], Lieuwen et al. [17], and Hubbard and Dowling [11], just to cite a few.

The idea of a feedback mechanism has gained favor by many researchers because of a criteria developed by Lord Rayleigh in 1878. If energy is added to the acoustic field with the right phase, then the acoustic field is excited, generating unstable pressure oscillations. Culick [2] describes the criteria developed by Lord Rayleigh to determine the proper phasing between the unsteady heat release and an acoustic wave. Rayleigh's criteria states that if unsteady heat is added to air at a moment of greatest compression, or is taken away at a moment of greatest rarefaction, then oscillations in the pressure field will result. If for some reason the flame begins to oscillate at a frequency near a natural acoustic mode of the system, and Rayleigh's criteria is satisfied, then a self-excited system will be created. The flame adds large amounts of energy in phase with the acoustics, thus creating an oscillating pressure field which further causes the heat release from the flame to oscillate due to the pulsation of the fuel/air mixture entering the flame. Rayleigh's criteria is easily applied to simple systems such as a Rijke tube, but for full scale gas turbine rigs apriori prediction of instabilities is impossible without detailed acoustic and combustion models. These predictive models are hampered by the complex non-linear phenomena involved in the combustion process.

2.2- Thermoacoustic Instability Solution Strategies

In addition to understanding the physics of TA instabilities, research is also being conducted to control these instabilities. As previously mentioned, making models to use in linear control strategies is difficult due to the non-linearities in the system. In general, both passive and active control may be used to control instabilites. Both control strategies have had some success in controlling TA instabilities, but no strategy has completely eliminated the problem.

2.2.1-Active Control Strategies

Active control involves time varying actuation of a control parameter to keep a system from becoming unstable. Active control requires a thorough understanding of the system dynamics, as well as identification of a system parameter which has the authority to actuate the system. Annaswamy [1] and McManus [19] provide reviews of the various control strategies used to date. Active control can be categorized into either open-loop or closed-loop control. Open-loop control actuation is not based on dynamic feedback from the actual system through a sensor, whereas closed-loop control actuation is based on feedback from a sensor. The control strategy used is dependent on the type of instability one is attempting to control. Open-loop control has been used by Paschereit [23] to oscillate the boundary layer in order to control large vortices formed by dump combustors , and also acoustically force the pressure field. Due to the non-linearities in the system, often open-loop control can not adapt to changes in the system because its control actuation is not based on feedback from the system. Therefore, closed-loop control has been the dominant active control strategy.

Numerous closed-loop strategies have been used to control TA instabilities. Zinn [33] provides an outline of active control including a theoretical analysis, general control techniques, and future development needs. The most common form of control uses information from a pressure transducer to generate a control signal for some type of actuation device. These devices include mechanical shakers to modulate the velocity field, acoustic sources such as speakers, and secondary fuel injectors. Using Rayleigh's criteria, these actuators attempt to drive the heat release 180° out of phase from the dynamic pressure measured by a pressure transducer in the vicinity of the flame. Mechanical shakers and acoustic drivers have only had success on experimental test rigs since they do not have the authority to control large amplitude pressure oscillations. Fuel modulation has been the primary control strategy used on large test rigs, even though there exists some problems with this form of control. Since the phasing of the secondary fuel is critical to controlling the instability, fuel must be injected very close to the flame so that the concentrated fuel mass is not allowed to diffuse into the surrounding mixture. Also, injecting fuel at one frequency can suppress that frequency, but excite another frequency. Other researchers, such as Richards [25], have controled flame instabilities experimentally by using a low frequency pulse which is not associated with the actual instability frequency. Many of the problems with fuel injection, and other forms of active control, arise from the fact that detailed dynamic models do not exist for the acoustics and combustion processes. To overcome these problems, adaptive control has been used by some researchers such as Vaudrey [33] and Padmanabhan [21] to adjust control parameters based on sensor information without the need for any analytical model.

A common problem with the control strategies introduced above is that they suffer from a lack of physically based models. With this realization, researchers have attempted to model the complex physics which occur inside the combustor. Many researchers including Culick [3] and Murray [20] have used a combination of experimental data, linear system theory, and non-linear analysis to create reduced-order models for combustion systems so that relatively detailed plant models can be used in active control systems. Detailed models are extremely complicated due to the highly non-linear nature of the combustion process and difficulties associated with identifying the proper coupling mechanism between the heat release and pressure field.

2.2.2 -Passive Control Strategies

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 cannot dynamically respond to any changes that may occur during operations. Many researchers including Annaswamy [1] have avoided passive control specifically for the reason that it can not adapt to changes in the system. Others, such as Zinn [33], 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 [9] 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 apriori. The resonator's practicality is limited by its inability to adapt to various operating conditions. Gutmark [8] used vorticity producing ramps to passively control how large scale vortices coupled with the heat release from the flame in a annular dump combustor.

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 [29], Straub [30], and Smith [27] have reported that axial adjustments in the location of the fuel spokes has a positive impact in eliminating thermoacoustic instabilities. As discussed previously, active control techniques have focused on the modulation of fuel flow to control the phasing relationship between heat release and the acoustic pressure field. The acoustic particle velocity modulates the fuel/air mixture at the fuel injection location. This fuel oscillation is transported down the injector to the flame front where the unsteady fuel flow causes unsteady heat release. Since the unsteady heat release occurs at the same frequency, it can amplify the acoustic particle velocity. In a passive sense, the delay time from the fuel injection location to the flame front is the parameter that affects the stability of the system. Straub has shown experimentally, and Steele has shown using CFD, that the time delay parameter is significant, but without developing a system model the physical effect of a time delay or delays is not known.

All of the control strategies previously discussed have some shortcomings mostly due to the fact that there is no comprehensive model describing the actual physical processes occurring during a thermoacoustic instability. This realization resulted in the development of a linear stability analysis technique which is a system-based approach to modeling thermoacoustic instabilities. Figure 1.2 shows one realization for modeling the self-excited system which incorporates the relevant blocks believed to control the system dynamics. The acoustic and flame dynamics are the two major components dominating the response of the system. Using such a system-based model, simulation results immediately show how the time delay affects the system since it is known that time delay adds additional phase to a system. This time delay will change the frequency where linear system theory would predict instability. Systematic changes to each of the model's component values will then provide essential information about the role of each component in the overall instability process.

2.3-Required Modeling Techniques for a System-based Analysis

In order to create a model for the self-excited system, each specific block in Figure 1.2 must be modeled and verified. Many researchers have generated models for various components of the system. Janus [12], Krüger [15], and Fleifil [6] have all developed dynamic flame models in order to capture the unsteady heat release from the flame. These models range from a simulation of the non-linear conservation equations for a well-stirred reactor to a full unsteady simulation using the Navier-Stokes equations. The other major system component which must be modeled is the acoustics. Researchers including Lovett [18], Paschereit [22], and Krüger [16] have created detailed acoustic models. Most acoustic models rely on a 1-D transmission line technique which assumes that standing waves form in elements which are connected by boundary conditions to form a transmission line. Other modeling techniques include finite-element models and lumped-element models. The simple models such as the lumped-element models are easy to implement but have many limitations including the frequency range over which they are valid. More complicated finite-element models have fewer limitations, but require more computation time. The last dynamic component of the system is the time delay element. Lieuwen [17] describes the time delay as the transport time from when fuel is injected into the system to when it burns at the flame front. Fannin [4] shows how single and multiple time delays affect the dynamics of the system. In the case of multiple time delays not only the phase, but also the magnitude of the system can be altered. Fannin defines multiple time delays based on multiple fuel injection locations, but there could also be multiple time delays created from an axial distribution of heat release with only one fuel injection location.

Krüger [16] provides an example of the general layout for a system-based model. Krüger uses a 1-D transmission line approach to generate the acoustic response while using 3-D unsteady CFD to find the dynamic response of the flame to a step input. A Nyquist stability analysis is performed on the open-loop system. The current work differs from that of Krüger because it will attempt not only to generate models for the various system components, but also to validate each component through model comparison with data. Validation results presented in this thesis will focus heavily on the acoustic component, while validation of the heat release and time delay are ongoing and will be presented at a later time. The other major difference between Krüger and the current work is that Krüger's approach simply provides a model of the system and does not provide a design tool to modify the system if its frequencies of instability pose an operations problem. It will be shown that the time delay is an adjustable parameter which can move the system phase crossings to areas of low gain, so that instabilities can be avoided. Multiple time delays can also act as notch filters to reduce the system gain in various locations. In summary, the overriding goal of the processes discussed herein is to combine analysis tools from various disciplines including linear system theory, acoustics, and combustion to optimize the modeling and stability prediction process. This process will ultimately result in a better physical understanding of thermoacoustic instabilities, while at the same time providing a realistic design tool to the gas turbine industry.