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OVERVIEW OF DIFFERENT APPROACHES FOR ACTIVE CONTROL OF COMBUSTION INSTABILITIES

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Abstract

This paper describes three different active control approaches for damping detrimental combustion instabilities that have been investigated at Georgia Tech in recent years. The first approach uses a closed loop active control system (ACS) that consists of a pressure sensor, a real time observer, a controller and a fuel injector actuator. Its unique components are the observer, which determines the characteristics of the most unstable combustor modes within a few (two to five) periods of the oscillations, and the fuel injector that employs a magneto-strictive actuator to modulate the fuel injection rate over a relatively wide range of frequencies. It has been shown that this ACS can effectively damp combustion instabilities over wide ranges of operating conditions on different combustors nearly instantaneously (~40μs). The second ACS damps combustion instabilities by "active" modification of the characteristic combustion time. This is achieved by use of a "smart" fuel injector with capabilities for changing the characteristics of the fuel spray. This, in turn, changes the characteristic combustion time in a manner that prevents coupling between the combustion process and acoustic oscillations, thus damping the instability. The advantage of this approach is that it damps the instability by a "one-time" change of the "smart" fuel injector setting. The third approach actively damps combustion instabilities by open loop, periodic, modulation of the fuel injection rate at frequencies that differ from the instability frequency. It is shown that modulating the fuel injection rate over specific ranges of frequencies results in near complete damping of the instability. Apparently, modulating the fuel injection rate at one of these frequencies "disrupts" the mechanism that drives the instability. While this approach is very effective, the manner in which it "operates" must be elucidated before it is used in practice.

1. INTRODUCTION

This paper describes three active control approaches developed and investigated at Georgia Tech to damp combustion instabilities. Combustion instability occurs when energy supplied by the combustion process excites large amplitude oscillations of one or more natural acoustic modes of the combustor[1]. These oscillations are problematic because they generally result in malfunction of one or more system components and, thus, mission/system failure. Consequently, considerable resources have been expended over the past fifty years on development of approaches that would prevent/damp these instabilities. Most of these efforts investigated passive control approaches consisting of, e.g., modification of the combustion process to reduce the energy that it supplies to the unstable modes and/or increasing the acoustic damping of the oscillations. Since the development of these passive control approaches proved to be time consuming and costly and their effectiveness was often limited to a narrow range of operating conditions of a *specific* combustor, significant efforts have been invested in the past twenty years to the development of active control systems (ACS) for damping combustion instabilities.

2. INVESTIGATED ACTIVE CONTROL SYSTEMS

The ACS discussed in this paper generally include of all or a combination of the following components: sensor(s), observer, controller and actuator(s). The objective of an ACS is to sense the occurrence of instability, identify its characteristics and take preventive action that would reduce its amplitude to lowest possible magnitude. While the potential advantages of ACS were recognized as early as the 1950s[2,3], most of the research in this field has been performed in the past twenty years[4,5]. This research was stimulated by the development of sensors, actuators, electronics and computing capabilities that made it possible to develop practical ACS, and the belief that a given ACS, perhaps with slight modifications, would be able to damp instabilities over wide ranges of operating conditions in different combustors. This would reduce the time and cost required to eliminate/damp future combustion instabilities in practical systems.

2.1 ACS Based upon Rayleigh's Criterion

The first investigated ACS[6] that was based upon Rayleigh's criterion[1], which states that periodic heating of an oscillatory flow 180 degrees out of phase with respect to the flow pressure oscillations damps the oscillations. Figure 1 shows a schematic of this ACS. It consists of a pressure transducer that measures the combustor dynamic pressure; an observer[7] that determines the amplitudes, phases and frequencies of a pre-specified number of the most unstable (i.e., largest amplitude) modes within several periods of the most unstable mode's oscillations; a controller; and a magneto-strictive actuator that modulates the flow rate of all or a fraction of the fuel stream with desired amplitude, phase and frequency. This ACS damps combustion instability by modulating the injection rate of a "control" fuel stream (supplied through the radial orifices in Figure 1) at the frequency of the most unstable mode and a (specified) control phase to generates "secondary" combustion process heat release oscillations out of phase with respect to the most unstable mode pressure oscillations as described by the red and black sine waves in Figure 1, respectively.

The ACS shown in Figure 1 injected a mixture consisting of 80% of the total fuel and all the air through circumferentially distributed, inclined orifices and the remaining 20% of the fuel, which was used to control the instability, through the radial orifices. The time dependence of the flow rate of the secondary fuel stream was controlled by the magneto strictive actuator whose length depends upon the magnitude of the magnetic field generated by the current passing through its coil. Passing AC current through the actuator's coil periodically modulated its magnetic field and, thus, its length. As the actuator's length periodically varied, it periodically changed the area of an orifice that supplied the secondary fuel, thus modulating its flow rate in a desired/controlled manner.

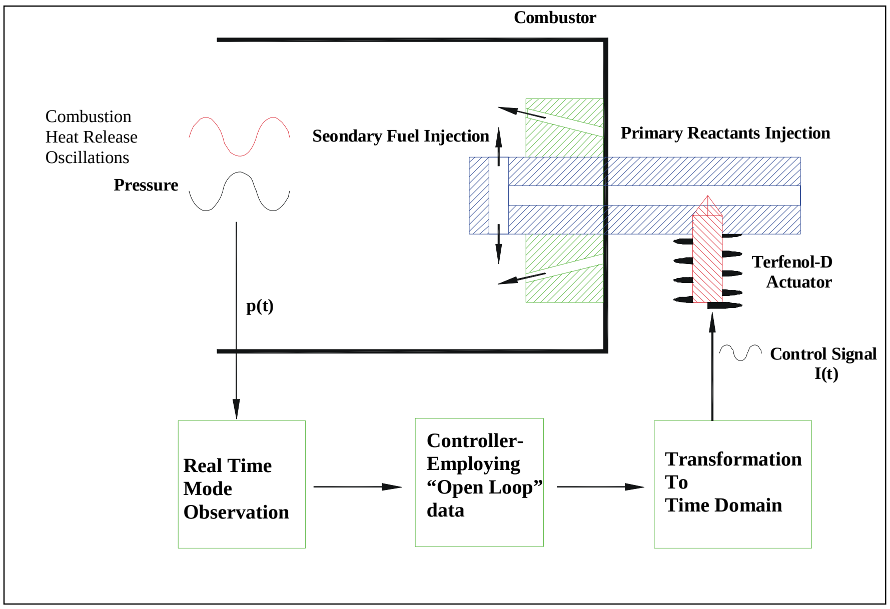

Figure 1. ACS based upon Rayleigh's criterion.

During operation, the controller determines the control current to the actuator using information supplied by the observer and data measured in separate tests that describe the open loop response of the combustion process; i.e., the former includes the amplitudes, frequencies and phases of a specified number of unstable combustor modes and the latter described the frequency dependence of the amplitude and time delay of the combustion process oscillations produced by periodic modulation of the fuel injection rate by the actuator in open loop tests[8,9].

Figure 2 describes typical performance of this ACS while damping instability in a gas rocket that burned methane and air at a mean combustor pressure of 100 psi. It shows that prior to activating the ACS at time t=0.1 sec, large amplitude (i.e., ~15 psi, peak to peak), shock-like, pressure oscillations were present in the combustor. In this test, the ACS only controlled the fundamental, ~400Hz. Mode of the combustor and Figure 2 shows that the instability was effectively damped 40 μs. after the ACS was turned on. The plots at the bottom of the figure show the FFT of the combustor pressure oscillations prior and after the ACS was activated. They show that: 1. large amplitude oscillations of the fundamental mode and its harmonics were excited by the instability; 2. by controlling the fundamental mode only it was possible to control all the unstable modes, indicating that the harmonics were driven by the fundamental mode via nonlinear processes; and 3. the amplitude of the fundamental mode was reduced by around 23db. The results presented in

Figure **2** clearly demonstrate that the developed ACS can effectively damp highly nonlinear instabilities nearly instantaneously without apriori knowledge of the characteristics of the instability.

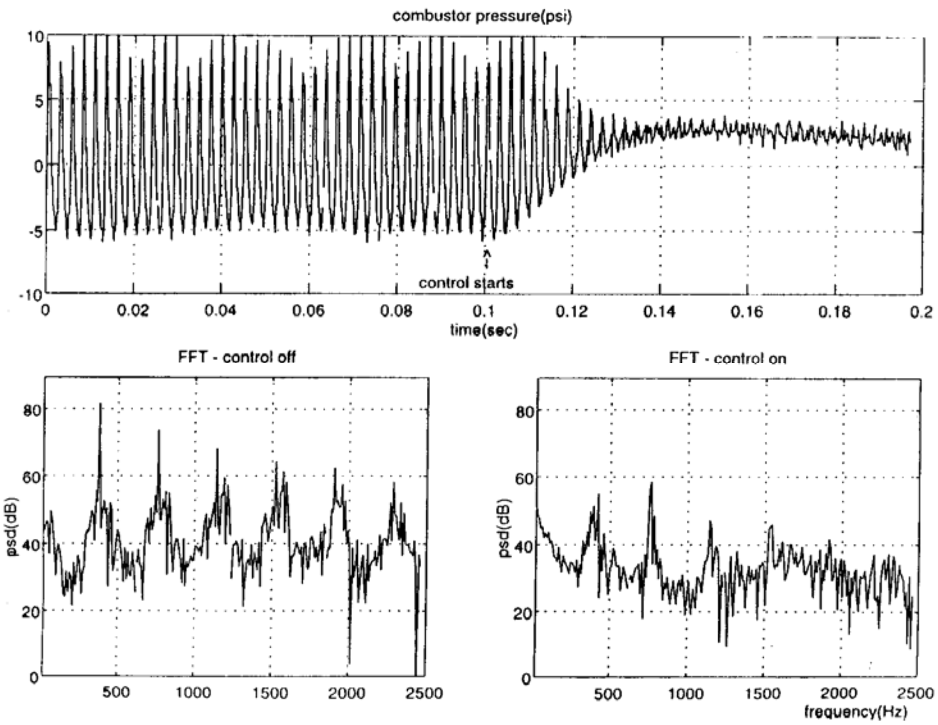

Figure 2. Description of active control of an instability with the Rayleigh based ACS.

2.2 Active, intermittent, combustion instability control

The second investigated ACS was based upon the knowledge that instabilities are driven when the characteristic combustion (e.g., evaporation time of fuel droplet, time period between injection and burning, etc.) and acoustic (i.e., period of one of the combustor's acoustic modes) times are of the same order of magnitude. This knowledge suggested that combustion instability could be damped if the characteristic combustion time could be changed during operation in a manner that will prevent this coupling between the combustion process and acoustic oscillations. It was then hypothesized that if the characteristic combustion time depended upon the fuel spray properties (e.g., shape and droplets size distributions), then this time could be varied by changing the spray properties using, e.g., a "smart" fuel injector that could control its spray properties. To investigate this hypothesis, the fuel injector shown on the left of

Figure **3** was developed and investigated. This injector is supplied with an axial fuel stream at the bottom and two "tangential" air streams whose total flow rate is fixed. The lower (left) and upper (right) air streams introduce the air at the injection points with clock- and counter-clock wise rotations through four tangential orifices, resulting in two counter swirling air flows at their injection planes within the injector. Tests with these injectors have shown that changing the ratio of the "lower" and "upper" air flow rates, denoted by the parameter K, while keeping the total air flow rated fixed, significantly changes the spray shape, but not the droplet sizes[10]. Specifically, it was shown that as K varied from low to high values (e.g., from 25/75 to 85/15), the spray changed from being nearly radial to a jet like shape.

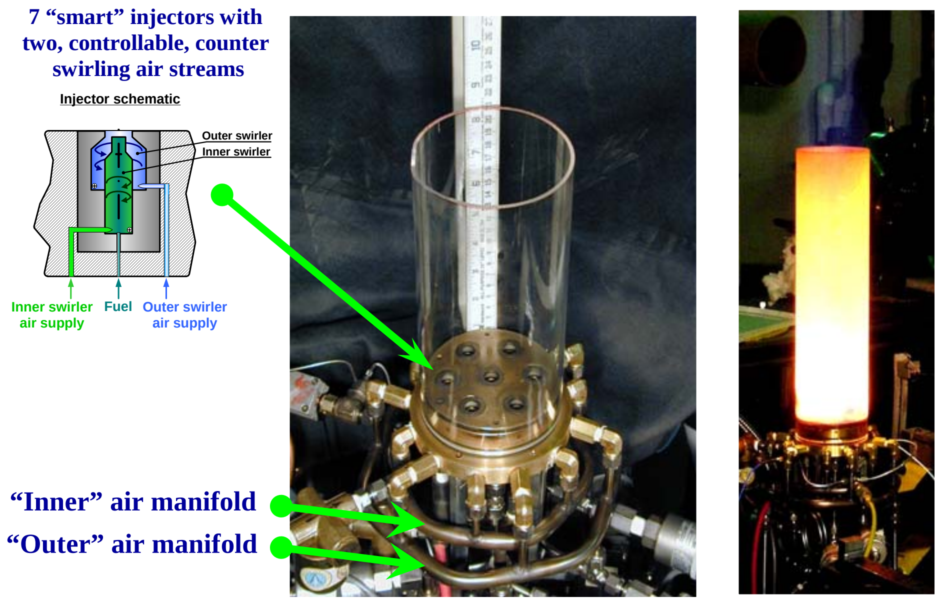

Figure 3. Setup used to study intermittent instability control.

The feasibility of the above discussed control idea was investigated in two combustors; the first having a single “smart” fuel injector in the center and the second consisting of seven “smart” fuel injectors, see

Figure **3**. Measured data obtained with the seven-injector combustor are presented in Figure 5. In this experiment, the combustor shown in

Figure **3** was initially operated with an equivalence ratio of .7 and K=80/20 that produced jet like sprays similar to the one on the left of the figure. At t~58 sec., the equivalence ratio was increased to ~1.2, resulting in the excitation of a ~4600Hz, first tangential mode instability. To damp this mode, the value of K was changed from 80/20 to 50/50 on all seven injectors, which “broadened” the sprays as shown in the figure. This was accompanied by nearly instantaneous damping of the instability. It was shown in a separate study, not discussed in this paper, that this approach also effectively damps axial instabilities.

While the above results were obtained using “human” control, better performance would most likely be obtained with using an ACS consisting of pressure sensors, a controller that would “understand” the system’s respond and actuators consisting of arrays of “smart” fuel injectors. Significantly, these results show that effective active control can be attained by changing the characteristic combustion time during combustor operation.

In one of the closed loop active control tests, the ACS described in Figure 1 had mistakenly modulated the control fuel injection rate at a frequency that differed from the instability frequency. Surprisingly, the observed damping was significantly higher than that attained using “conventional” closed loop ACS; i.e., ACS that control instabilities by modulating the fuel injection rate at the frequency of the most unstable mode. To further investigate the effect of the frequency of fuel injection rate modulation upon the effectiveness of active control, we have investigated the response of the combustor to modulation of the fuel injection rate at different frequencies that were chosen “arbitrarily” without any regard to the operating conditions in the combustor. This study was performed using the gas turbine combustor setup shown in Figure 4. When operated uncontrolled, this combustor experienced very large amplitude, 400Hz. longitudinal instabilities over a wide range of operating conditions.

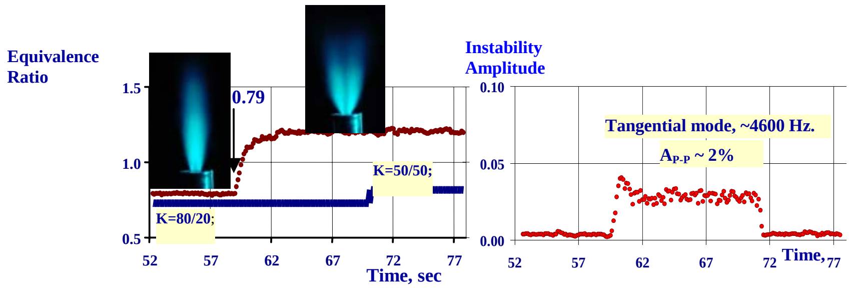

Figure 5. Control of first tangential mode instability by varying the parameter K.

2.3 Open loop control of combustion instabilities.

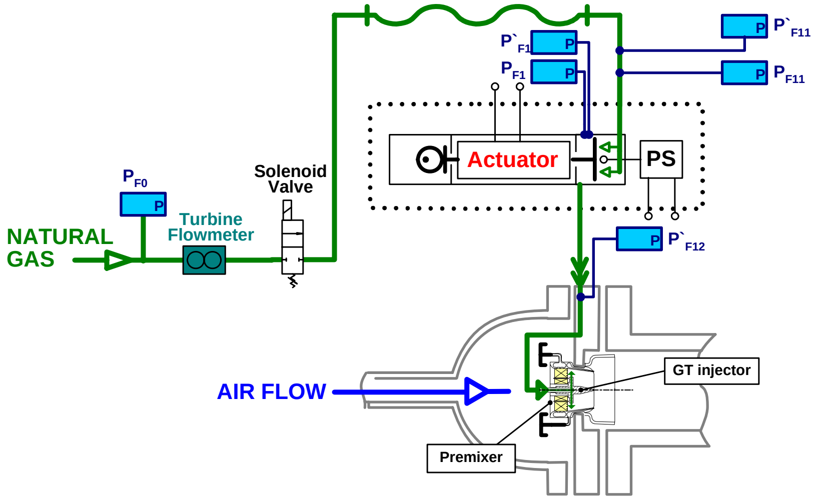

Figure 6. A schematic of the gas turbine combustor setup used to study open loop control.

In the reported test, the entire fuel flow rate was modulated by a magneto strictive actuator upstream of the injector. As the test progressed, the fuel flow rate modulation frequency was linearly varied from ~500 to ~50 Hz. over a period of 520 sec. without any "feedback" describing the "state" of combustor oscillations. Simultaneously, the amplitude and frequency of the combustor oscillations were also measured. The results are described in

Figure 7 whose top plot describes the time dependence of the amplitude of the combustor pressure oscillations (note: on a logarithmic scale) and bottom plot describes the time dependence of the frequency of the fuel modulation (blue) and combustor oscillations (red). Interestingly, the latter shows the presence of the ranges of frequencies that 400Hz. mode is excited in the combustor in spite of the fact that the forcing (i.e., fuel modulation) occurred at a different frequency. When this occurred, the combustor generally experienced large amplitude instabilities of its 400 Hz. fundamental mode. The bottom plot also shows, however, the presence of frequency ranges (e.g., between 300 and 370 Hz.) in which the combustor oscillations occur at the forced frequency and the 400Hz. instability is missing. In these instances, the "forced" combustor oscillations amplitudes are significantly lower that the 400Hz. natural acoustic mode oscillations. In fact, the amplitudes of these “forced”, non resonant oscillations were small so low that they would most likely not affect the combustor operation.

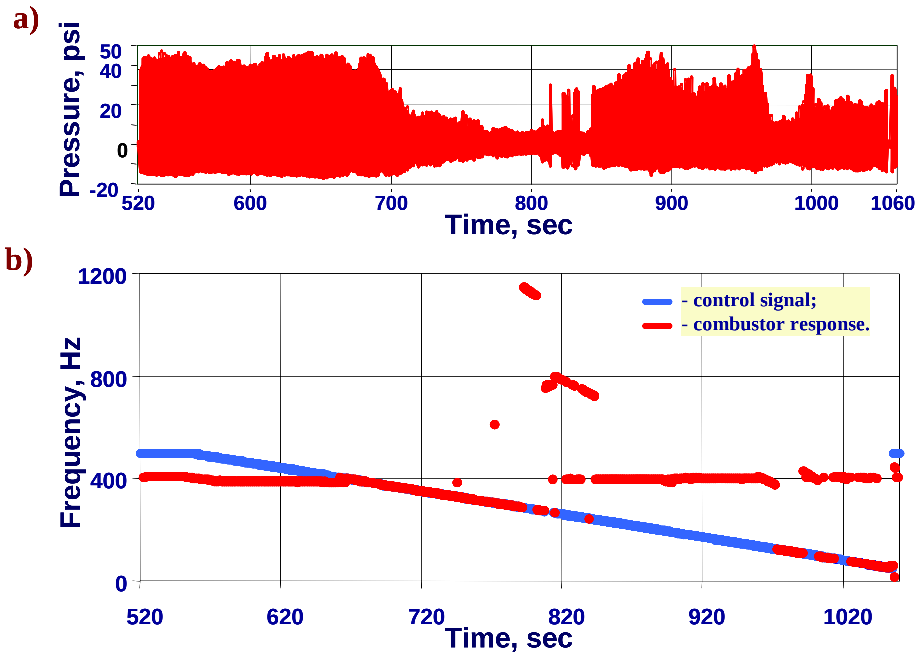

Figure 7. Time dependence of the pressure and frequency of the combustor oscillations during an open loop control test in which the fuel modulation frequency was linearly varied between 50 and 500Hz.

These results strongly suggest that “forcing” the combustor at certain “non resonant”, frequencies may completely damp resonant instability while exciting low amplitude, “harmless”, non-resonant forced oscillations in the combustor. Clearly, research that will provide understanding on how to identify these non resonant frequencies is needed.

3. CONCLUSIONS

It is noteworthy that two out of the three ACS discussed in this paper were based upon *qualitatively* understanding of the conditions that must be satisfied in unstable combustors; i.e., the heat release and pressure oscillations must be in phase (Rayleigh’s criterion) and the characteristic combustion and acoustic times must be of the same order of magnitude. Nevertheless, these ACS effectively damped combustion instabilities that were controlled by different mechanisms. It should be further noted that while the first ACS discussed in this paper used measured open loop combustion process response data to determine the control signal to the actuator, it has been shown elsewhere[11] that this ACS can also effectively damp combustion instabilities using an adaptive control approach. Finally, it is important to reiterate that while the third ACS discussed in this paper demonstrated that considerable damping may be attained by use of open loop modulation of the fuel flow rate at certain non resonant frequencies of the combustor, it is of utmost importance to develop an understanding of how to select these frequencies and how they are related to the processes/mechanism that drives the instability.

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