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ARMARKOV Adaptive Control of Self-Excited Oscillations of a Ducted Flame [1]

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Abstract

Active control of thermo-acoustic instabilities represents a significant challenge and opportunity for feedback control technology. In this paper, we experimentally apply ARMARKOV adaptive control to a ducted flame with a servovalve actuator. This approach requires an identified model of the transfer function from the control input (modulated air stream) to the performance variable (microphone). This identification was performed under fuel-burning conditions. No analytical modeling was used for controller analysis or synthesis. The ARMARKOV adaptive controller suppressed the fundamental component of the limit cycle oscillation.

1 Introduction

Active control of combustion provides significant opportunities for feedback technology, but is also extremely challenging. The complex combustion process involves fluid dynamics, thermal effects, acoustic interactions, and kinetic effects. Most gas turbine engines exhibit combustion-induced instabilities under some operating conditions. These instabilities can reduce efficiency and unnecessarily restrict the region of operation. Passive control techniques are effective for only a limited range of conditions.

In the present paper we adopt an adaptive control approach that reduces the need for modeling for the purposes of controller tuning. The underlying assumption is that suitable sensors and actuators are available with the necessary authority and architecture for reducing the acoustic oscillations. Our starting point for this work is the ARMARKOV adaptive control technique developed in [1].

Here we report the results of an experimental application of ARMARKOV adaptive control on a ducted flame. The experiment utilizes a pair of microphones for the performance and feedback sensors, while the actuation is achieved by means of a high bandwidth servovalve. After identification of the secondary path dynamics under fuel-burning conditions by means of recursive ARMARKOV identification, the ARMARKOV adaptive controller was implemented on a DSP-based real-time processor for closed-loop operation.

2 Description of the Ducted Flame Experiment

Figure 1: The lower portion of the duct, with "T" section and grid of burner visible

The flame is produced by a Meeker burner (Fisher Scientific part number 39105) which is 7.75" high and has separate, adjustable inlets for fuel and air. The flame resides on a 1.625" diameter circular grid at the top of the burner. For fuel, we used commercially available propane.

The duct (Figure 1) is constructed of steel pipe mounted vertically on an optical table. The lowest section is constructed of 4" inner diameter pipe to accommodate the base of the burner. This is followed by a reducer which narrows the inner diameter to 3". A "T" section of 3" inner diameter pipe is situated such that the flame can be observed. Above the "T" is 4' of 3" inner diameter pipe.

Air for the experiment is provided by a 40 psi supply. This line is split such that the majority of air passes directly to the burner, while the remaining air passes through the servovalve and then rejoins the main air stream prior to reaching the burner.

An HR Textron servovalve, used in [2], model 27A1 is used for air flow modulation. This valve is rated at

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8 scfm with a bandwidth (to 3 dB rolloff) of approximately 200 Hz.

Sensing was performed using two Radio Shack omnidirectional microphones, model Optimus 33-3013. The microphone for the feedback signal y is at the base of the burner at the bottom of the duct, while the microphone for the performance signal z is located at the same height as the flame. Acoustic measurements further along the duct were precluded by the high heat levels.

The control processor was a dSPACE 1003 C40 processor with a 300 MHz Alpha board. This processor was used in [1] for active noise control experiments. The ARMARKOV adaptive algorithm is programmed in C as a Simulink S function.

3 Experimental Results

Minor adjustments of the fuel and air flow rates were made to produce significant acoustic response. It was verified that this response could not be produced by the air flow rate alone, confirming the role of heat release in producing an acoustic instability.

A typical spectrum of the performance microphone signal is shown in Figure 2. The objective of the adaptive control experiment was thus to reduce the amplitude of this limit cycle without significantly raising the amplitude of other response harmonics.

To apply ARMARKOV control, we identified the secondary path transfer function, that is, from the control u (the servovalve-modulated air flow) to the performance microphone z. The identification was performed using the technique of [3] and was carried out under both air-only and fuel-burning conditions. Although the identification performed under air-only conditions yielded a high quality transfer function, the subsequent adaptive controller proved to be unstable. This illustrates that capturing the dynamics of the combustion process is essential for meaningful control.

A model of order $n = 25$ was constructed, with $\mu = 55$ Markov parameters in the numerator polynomial. The identified model was of marginal quality as expected due to the ambient noise of the acoustic instability. Using the identified model of the secondary path transfer function, we applied the ARMARKOV adaptive controller to the ducted flame. The sample rate was chosen to be 1000 Hz. The controller order n_c was set at 25 with $\mu_c = 55$ Markov parameters in the numerator polynomial. The performance window length p was chosen to be 4.

Figure 3 shows the open-loop and closed-loop spectra of the performance signal z. The amplitude of the limit cycle oscillation was reduced by up to 18 dB.

4 Conclusions

The approach to active control of a ducted flame described above is based upon the ARMARKOV adaptive control algorithm of [1]. As such, the method requires a model of only the secondary path transfer function, from the control input to performance variable. No attempt was made to analytically model this transfer function. Rather, an ARMARKOV-based identification algorithm was used to construct a model of this transfer function under fuel-burning conditions. The algorithm exhibited convergence in approximately 15 seconds and achieved up to 18 dB of suppression of the fundamental limit cycle component.

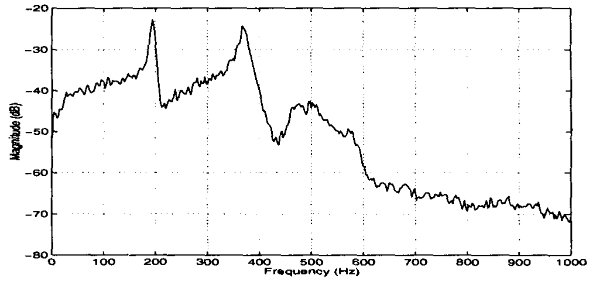

Figure 2: Open-loop frequency response

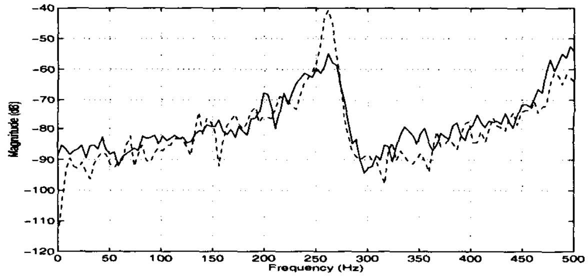

Figure 3: Open-loop (dashed line) and closed-loop (solid line) frequency response

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