A Comparison Between Frequency and Amplitude Modulated Adaptive Control of a Non-Premixed Flame

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Abstract

Acoustic forcing of a laminar non-premixed flame issuing from a Wolfhard-Parker slot burner affects soot production in the flame and thus its luminosity. This research details how the relationship between acoustic forcing and the luminous response can be used to implement full closed-loop adaptive feedback that actively controls the flame luminosity. Results show that in an open-loop configuration both the frequency and amplitude of an acoustic square-wave produce large overall changes in flame luminosity and that both methods may be useful in implementation of a closed-loop controller. A one step-ahead adaptive control law with least-mean-square recursive parameter identification was used to compare the control performance using frequency and amplitude modulation schemes. For the frequency modulation case, the adaptive controller changes the frequency of the acoustic wave and for the amplitude modulation the amplitude is changed at every control period to try to attain the desired luminous output from the flame. Several test cases were run including fixed-point, linear, square wave (multiple step), and fixed-point with disturbance, in an effort to determine which control implementation best met the control objectives. The results from the tests indicate that the frequency modulated control input was able to operate at higher control frequencies and also tracked the desired output more closely. The relatively large difference in performance found from these trials demonstrates the importance of selecting the proper actuation for a particular system and the potential benefits in relating the actuation mechanism to the combustion process.

Introduction

With the advent and increasing sophistication of computers, many modern combustion systems have begun to benefit from precise computer controlled fuel injection, air injection, and product removal. Despite the precision, however, these systems lack all but the most basic control over the combustion process. In addition, the degradation of the components used in the high temperature combustion environment alters their performance, but only rarely do combustion systems adapt themselves to the changes.

One area of research that has the potential for pollutant reductions, efficiency improvements, and overall flame stability despite perturbations of reactants and system degradation, is combustion control through the exploitation of modern control theory. While still in their infancy, applications of control techniques to modern combustion systems may permit a rigorous approach to improving and maintaining combustion systems peak performance. Gutmark and co-workers have an array of papers detailing the control of flames through acoustic forcing [1, 2, 3]. Their work shows a relationship between the structure of the flame at the flame zone and acoustic excitation of the fuel and air. Some of the work focuses on classical amplitude modulation and phase-locked active controllers while other research focuses on neural networks in active combustion control [4, 5]. The work of Annaswamy and Ghoniem demonstrates that dynamic feedback models, including an acoustic system with linearized heat release can be used to capture and control instability dynamics of simple combustors [6, 7]. Much of the previous work in combustion control, because it has been motivated by instabilities in engines and rocket motors, involves acoustic coupling between the flame and the geometry of the combustion chamber (see, for example, [8]–[17]). To begin addressing other potential combustion control environments, this paper explores modern control techniques in the context of a simple unconfined combustion system. Specifically, we compare the performance of two different strategies for controlling a laminar non-premixed flame and then we suggest a relationship between that performance and the possible mixing and flame dynamics.

Experimental Apparatus

Wolfhard-Parker Slot Burner System

Our unconfined flame system is a two-dimensional Wolfhard-Parker slot burner. The burner, shown in Figure 1, is similar to the burner used by Smyth *et al.* [18, 19]. It consists of two rectangular air ports sandwiching a central fuel port slot. The two air ports are 16 mm wide by 41 mm long and the central fuel port is 8 mm wide by 41 mm long. Glass beads fill each of the three ports to produce uniform fuel and air flow. The air and fuel flow rates are controlled by Brooks Instruments flow meters calibrated for air and methane, respectively. Three four inch sub-woofer speakers (the actuators) inside hemispherical metal housings, connected to the burner as shown in the figure, provide acoustic fuel or air forcing in the system. Fuel modulation has been reported as an effective control point in combustion systems [20, 21]. The sensor is a silicon photodiode used to measure the flame luminosity. The photodiode is positioned sufficiently far from the flame to ensure a global measure of its light emission. The burner is housed within a hood with side walls fabricated from cloth, sheet metal rear wall and top, and a sliding acrylic front access/viewing wall. The cloth sides allow ambient air to enter the hood with minimal perturbation to the flame. At low frequency forcing, the flame can be made to flicker at a regular frequency, matching the natural buoyant plume frequency. Under these conditions enhanced peak soot production has been observed [22, 23]. At higher frequency, however, the flame takes on a premixed character, and soot does not form.

Control Apparatus

Figure 2 shows a schematic of the burner control apparatus. The system contains a single 486DX-33 computer which serves as both the controller and recorder. It performs all computations for driving the speakers, in addition to collecting the inputs to the system and outputs from the sensor. The output function of the computer uses two digital to analog boards. A computer program generates up to three different waveforms for output through each channel to the system actuators (fuel and air speakers). In addition to independent frequency control for each channel, the program also allows independent phase and amplitude control. The analog outputs pass through a power amplifier to the speakers attached to the Wolfhard-Parker slot burner. The outputs from the amplifier are also routed back to the computer for storage as system inputs. Collection of the amplified signal as an input rather than the original signal is important as it removes the need to include the dynamic response of the amplifier in identification techniques. The sensor (in this case a photodiode) measures the response of the flame to the system inputs. The amplified sensor signal is recorded by a sample and hold board connected to an analog to digital board within the computer. The computer uses this recorded data to complete the control loop required for active closed-loop control. Further details of the experiment appear in [24].

Control Approach

In order to develop a strategy for unconfined flame combustion control, we begin with a one-step-ahead adaptive control algorithm, including recursive parameter identification. This method has a standard adaptive least-mean-squares control formulation (see [25] or our previous work [24, 26, 27]) and serves as a baseline control technique that can be used to study the effectiveness and feasibility of advanced control techniques to this problem. We start with a relatively simple technique in the hope that the interactions between the combustion process and active control can be understood well enough to lead to more systematic modeling and control of similar processes. In particular, we expect adaptive identification methods that yield low order time varying models from the input/output data to eventually contribute to a better understanding of the underlying processes. Briefly, the technique used is an indirect adaptive control method combining a basic recursive least square (RLS) identification and a modified one step ahead control method. The cost functional, in addition to traditional square of the error terms, includes a term penalizing large changes in the value of the control. Recursive parameter identification continuously adapts in order to predict (using a locally linear model) the system response to actuator inputs. Meanwhile the control uses these parameters (and the system model they help construct) to bring the actual output to the desired output in one step.

The two control strategies compared both use the one-step ahead approach, but they are using frequency or amplitude modulated acoustic waves as the control actuation. Hence, the frequency modulated control scheme allows the controller to modify the frequency of a fixed amplitude acoustic wave to achieve the desired goal; the amplitude modulated control scheme allows the controller to modify the amplitude of a fixed frequency acoustic wave to achieve the desired goal.

Results and Discussion

Open-loop responses of the burner to fixed-amplitude variable-frequency and fixed-frequency variable-amplitude actuation are shown in Figs. 3 and 4. The open-loop testing determines the range of output values of the system for a range of input values. These values can then be used for demands of closed-loop control. A 7.2 cm^3/s fuel flow rate and a co-flowing 340 cm^3/s air flow rate create the baseline experimental conditions. Figure 3 details the relationship between the luminous output of the flame within the acoustic driving frequency range of 0–100 Hz at an amplitude of 10 V_{p-p} and over the amplitude range of 0–12 V at a fixed frequency of 100 Hz. The fixed amplitude (or frequency) is chosen to provide sufficient luminosity change over the frequency (or amplitude) range. The trend, traversing the frequency range, is a decrease in luminosity with increased acoustic frequency. The region around 10 Hz contrary to this overall trend corresponds to the natural flicker frequency of the flame [19]. The luminosity is reduced by more than 95% with an input acoustic forcing greater than 50 Hz. The trend for the amplitude experiment is a similar decrease in luminosity with increased acoustic input power. The nondimensionalized luminosity is reduced by more than 95% with an input voltage greater than 8 V_{p-p}.

Figure 3 shows that a correlation exists between both the input frequency and input amplitude of the acoustic forcing and the luminous output of the non-premixed flame. Under amplitude modulation, however, the luminosity changes very little until the amplitude reaches approximately 4.5 V. After this value, the luminosity diminishes rapidly until, at approximately 6 V, the luminosity has reached its lower limit. The luminosity decreases more steadily in the frequency modulated case. Microphone measurements of the sound energy produced with increasing amplitude (at 100 Hz) and increasing frequency (at 10 V) over the ranges studied show a nearly equal linear increase in both cases. There is a plateau at low amplitudes (less than 2.5 V) where increasing the input voltage seems to have little effect on the sound energy, but the plateau does not extend to the 4.5 V level where the large change in luminosity begins to occur. These results suggest, therefore, a lower threshold amplitude requirement before the flame responds, but no lower threshold frequency. Based on the open loop information, a control implementation using either technique should be capable of full-scale luminosity control.

The performance tests selected to compare the two different control implementations are the ability of the controller to: (1) maintain a fixed luminosity, (2) move at a constant rate between selected luminosities, (3) track a desired square-wave luminosity profile, and (4) maintain a fixed luminosity despite external disturbances to the system. The performance measure will be the standard deviation of the error between the desired and actual flame luminosity.

For the closed-loop control cases run below, every attempt is made to keep the operating conditions the same to help ensure a valid comparison. The only deviation from this is in the speed of the controller. Previous experiments showed that the frequency modulated controller could be operated at significantly higher rates than the amplitude modulated control. In these experiments, the frequency modulated controller operates with a control period of 100 ms while the amplitude modulated controller operates with a control period of 500 ms. Attempts to operate the amplitude modulated control at higher rates resulted in unacceptable performance. Although the controller can be of arbitrary order, we used a first order model (i.e., one based on a single prior input/output pair) to maximize control update speed. Prior work [24] suggested that a 10th order model can adequately capture the temporal luminosity variation of a regularly flickering flame, but that a first order model is superior to one of 2-3 orders for controlling the average luminosity.

Figure 4 shows the temporal luminosity response of the system using a first order control (Fig. 4a – frequency modulated; Fig. 4b – amplitude modulated) with a desired luminosity of 0.44. The standard deviation of the error between the desired and actual luminous outputs is 0.062 and 0.12 for the frequency and amplitude modulation respectively. Several additional cases were run with different desired luminosity values (0.074, 0.22, 0.71, not shown) resulting in overall standard error deviations of 0.074 and 0.16. Thus, the frequency modulated control implementation is substantially better at holding a desired set point luminosity.

Figure 5 details the temporal response of the system to a requested square-wave luminosity profile with a period of four seconds and a desired output that varies between 0.025 and 0.81. The standard deviation of the error is 0.31 and 0.35 for frequency and amplitude modulation, respectively. For a square wave request that varies between the maximum and minimum flame luminosity points, the controllers are nearly equivalent in performance.

Figure 6 reveals the luminous response of the system when facing a desired linear-ramp luminosity profile. The desired profile starts at 0.81 and decreases to a value of 0.025. The standard deviation for this control is 0.08 and 0.45 for frequency and amplitude modulation, respectively. Figure 6b shows a plot for the amplitude modulated control scenario. In this case, amplitude modulated control does an extremely poor job relative to frequency modulation.

Finally, Fig. 7 shows the disturbance rejection properties of the two controllers. The conditions are the same as in previous tests except that after thirty seconds into the operation of the controller, the fuel flow rate is changed nearly 70% from 7.2 cm^3/s to 12 cm^3/s. In Fig. 7a there is a noticeable change in the luminous output of the flame after 30 seconds. The control then brings the luminosity back to the desired value over the next 30 seconds. The standard deviation for this trial is 0.10. In Fig. 7b, after the disturbance, the amplitude control brings the luminosity back to the desired value more quickly than in the frequency modulated case. The fluctuations overall are larger however, producing a standard deviation for this experiment of 0.15 or 50% greater than for the frequency modulated control.

The behavior observed during the closed loop testing is consistent with the characteristics observed in the open loop results. In frequency modulation, the reduction in luminosity occurs over a wide input range, while in amplitude modulation, the same reduction in luminosity occurs in a very small region of input. Because the luminosity of the flame is very sensitive to changes in amplitude around this region, low order closed loop control desiring an intermediate luminosity value can be plagued by large fluctuations resulting from small deviations in amplitude. The frequency modulated control, however, being less sensitive to small changes, is less likely to face large fluctuations. For fixed point and linear tracking the amplitude modulated control performs poorly when compared with the frequency modulated control. When the desired goal is to track a square wave that is at the two extremes of the luminosity, however, the amplitude modulated control performs reasonably well since operation in the sensitive region is avoided.

The control results provide clear guidance that frequency modulation is more predictable than amplitude modulation for the flame studied. It seems that the flame's luminosity production can be more closely approximated by a first order model of the frequency input than of the amplitude input. The relatively higher sensitivity of the luminosity to amplitude change may require a higher order model or one focused more closely on the effective range of actuation. Nevertheless, this behavior must reflect the fluid mechanics of the process controlling luminosity. As mentioned above, the luminosity change occurs through mixing of the fuel and air. Without acoustic input the flame is a free diffusion flame with the requisite soot incandescence and luminosity. At the maximum acoustic input, we generate enough mixing near the burner surface to produce a premixed methane/air flame with virtually no soot and only low light levels of chemiluminscence. One possibility, suggested by the control study, is that the vorticies generated by the acoustic pulsation gradually and predictably increase their interaction (and their mixing performance) as their spacing decreases with increasing frequency. A similar predictability does not occur with increasing amplitude at fixed frequency, suggesting a different, perhaps more complex mixing relationship.

Summary and Conclusions

The goal of this research was to compare the performance of two different active control strategies on the luminous response of a laminar non-premixed flame issuing from a Wolfhard-Parker slot burner. The actuation for the system was acoustic perturbation of the upstream fuel and air flows. The comparisons made between the two implementations were based upon tests that represent classical performance measures of controllers in the form of fixed or set point control, tracking linear trajectories, repeated step response, and disturbance rejection.

Overall, the adaptive controller capably proved that it could manipulate the flame to achieve a fixed or time varying luminosity and that it could also accomplish this in spite of external disturbances. Comparing frequency and amplitude modulation showed that the frequency modulated control implementation was able to operate at higher control frequencies than its amplitude modulated counterpart. The results also showed that frequency modulation control performs better than amplitude modulation control. In every case, the frequency modulation had a standard error deviation less than for the amplitude modulation control performing the same task. These findings suggest that for a given controller and combustion system, the actuation mechanism plays an important role in the speed and performance of control. Modeling such mechanisms will be a forward step toward improved combustion control methods.

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