AJCPP 2008
March 6-8, 2008, Gyeongju, Korea

Active Control of Flame Oscillation in Lean Premixed Burners by Phase-Controlled Sound Waves

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Keywords: Premixed Burner, Combustion Instability, Active Control, Acoustic Waves

Abstract

The objective of the present study is to actively control the flame oscillation in the experimental lean premixed methane burner by the phase-controlled sound waves. The authors propose the methodology of generating the phase-controlled sound waves by directly sensing the preferential frequency and generating the sensor-triggered sound waves with fixed optimum phase difference with the flame oscillation. The real-time controller is implemented in the present study, and the combustion noise reduction is achieved. The reduction is 20dB at peak frequency and 13dB in the OASPL.

Introduction

Research and development of low-NOx burners is intensively under way recently in order to reduce the impact of the exhausted NOx on the global environment in the industrial and aeronautical gas turbine applications. Lean premixed combustion or direct injection of fuel with a strong swirl is effective for the low NOx emission. In recent years, the lean and low temperature combustion is widely and extensively used to reduce the NOx exhaust gases. The lean-remixed (LP) burners have less cooling holes or secondary air flow than the conventional gas turbine engines, because the temperature of combustion is kept lower by lowering the equivalence ratio. Therefore, the mechanical structure of the gas turbine engines becomes simpler. The lean premixed combustion invariably brings about the tendency of intense flame oscillation and/or flame instability, which may lead to the short-lifeness of the burner, the quenching of the flame, and/or the breakdown of the system at worst.

From old days, the instability or oscillation of the combustion flame have been observed in stoichiometric or rich-burn devices, such as afterburners, rockets, and ramjet engines. These instabilities and oscillations have been stabilized by backward-facing steps, bluff bodies or acoustic liners. Such strategies to stabilize the flame oscillation are called passive control[1].

To suppress the combustion oscillation, in addition to passive control described above, the active control is also in use. In the passive control, suppression of oscillation is performed by devising structure geometry of burners. This method has a merit that structure of the burner remains simple, but it has a demerit that it needs new design or adjustment from system to system. For example, a large suppression effect is obtained under certain conditions may not be achieved in other conditions. So the effect of stabilization is considerably limited and it may be difficult to use the passive control methods under the wide operating conditions.

On the other hands, compared with passive control strategies, the active control is usually easier to implement and capable of working in broader operation ranges. Although, it needs many components such as actuators, sensors and controllers to suppress flame oscillation. But it has a merit that, once the system is implemented, it is comparatively easy to adapt to other systems. In this study, the active control that has the wide application range is used to suppress the combustion oscillation.

The active control methods are categorized by the controller into the LMS, LTR, Phase-shift and LQG. As for the actuators, they are categorized into the second fuel injection and loudspeaker, where the former is used for the lower frequency oscillations and the latter is used for the higher frequency oscillations. The gas turbine burners of aero engines are smaller in comparison with those of the industrial gas turbines, and may have the higher frequency oscillation. The loudspeaker is used as an actuator in this study. The frequency range of the combustion oscillation which will be discussed in this study is from around tens Hz to around several hundred Hz.

The objective of the present study is to actively control the flame oscillation in the experimental lean premixed methane burner by the phase-controlled sound waves. The phase-controlled sound waves are used since it is understood that the flame oscillation occurs due to the interaction of the heat release and acoustic pressure waves and the phase plays an important role as indicated by the Rayleigh’s criteria. Among many papers [2)-6)] on the active control of the lean premixed combustion instability, a couple of papers are published using the phase controlled sound waves, but they inevitably implements the phase shift by generating the control sound with the time lag corresponding to the control frequency and phase. The preferential frequency depends not only on the system but also on the operating conditions. In this paper, the authors propose the methodology of generating the phase-controlled sound waves by directly sensing the preferential frequency and generating the sensor-triggered sound waves with fixed optimum phase difference with the flame oscillation.

Criteria for Combustion Oscillation

The temporal integral of the product of the heat release and pressure fluctuations is proportional to the generated energy in the combustion oscillation. According to Lord Rayleigh, the condition for the combustion oscillation to occur is

$$\oint HPdt \geq 0 \ ,$$

where H is the heat release fluctuation by combustion, and P is the pressure fluctuation in the combustion chamber. If the left hand side value is positive, the energy of combustion is accumulated to work for the oscillation to occur. On the other hand, if its value is negative, the combustion oscillation is attenuated. When the fluctuations behave in a sinusoidal manner with the frequency f, the condition is rewritten as

$$\pi p' h' \cos\phi \geq 0 \ ,$$

where ϕ is the phase-lag of the heat release oscillation against the pressure oscillation, p' and h' are the amplitudes of the pressure and heat release fluctuations, respectively. Then the combustion oscillation occurs for $-1/2\pi < \phi < 1/2\pi$ and does not occur for $-\pi < \phi < -1/2\pi$ and $1/2\pi < \phi < \pi$. Note here that the phase ϕ is closely related to the occurrence of the combustion oscillation and the optimum phase excitation of the fuel may result in the suppression of the combustion oscillation.

Experimental Setup

Figure 1 shows the overview of experimental setup. The combustion rig is depicted at the center. The methane supplied from compressed gas bombe via the mass flow controller and the air supplied from the compressor via the separate mass flow controller are mixed in the premixer. The pressure history of the flame oscillation is measured by the microphone set at the top of the burner chamber. The data is taken into the PC, and processed to generate and output the control signal to the loud speaker

Figure 2 shows the premixed burner used for the experiments. The methane-air premixed gas supplied from the lower premixer burns in the combustion chamber. The bluff body is used as a flame holder. The loud speaker used as the active control actuator is connected to the premixed gas feed pipe via the T elbow. The size of this burner chamber is 600mm x 150mm x 150mm, and the exhaust port is located at upper position with a cross sectional area of` 75mm x 75mm. On the side walls of the burner chamber, there are three optical-access glass windows and one solid metal wall with a hole for ignition. The combustion power is approximately 5 kW.

Next the characteristic of the flame oscillation in this burner is to be discussed. Figure 3 shows the frequency response of the flame oscillation in this chamber without control. When the flow volume rate of the premixed gas is 100 L/min and the equivalent ratio is 0.8, the combustion noise of flame oscillation is 131dB at the overall sound pressure level (OASPL). There is the prominent frequency peak at 153Hz. This frequency is regarded as the Helmholtz resonance frequency. It is found that the sound pressure level of this frequency is dominant in the combustion noise.

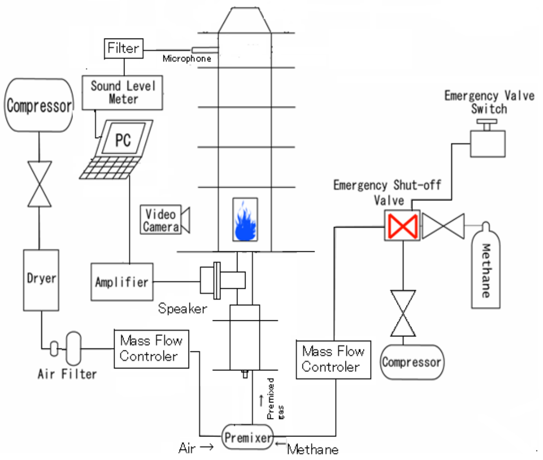
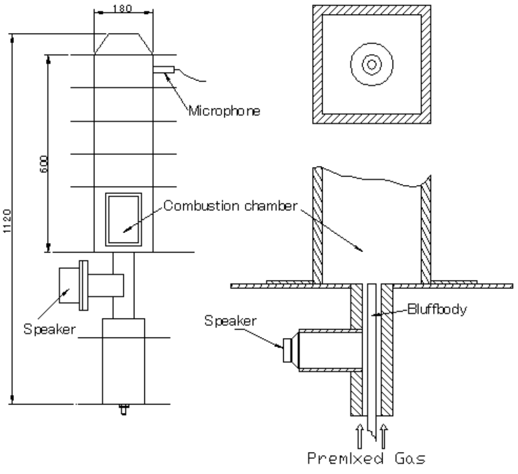


Fig. 1 Overview of experimental unit



a) Overview b) Flameholder

Fig. 2 Combustion rig

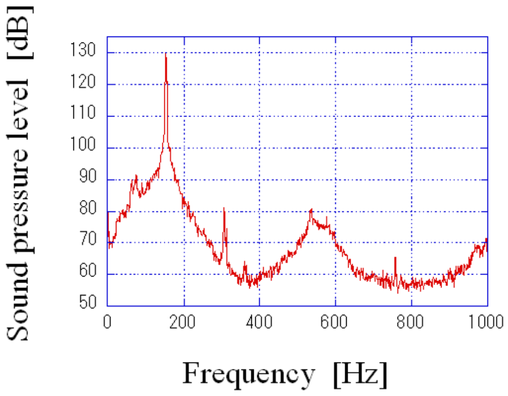


Fig. 3 Frequency characteristic of combustion

Control hardware and software

In order to generate the phase-controlled sound, the field programmable gate array (FPGA) board (National Instruments PCI-7831R) is used. The FPGA is the programmable LSI just like changing a large number of switches. Coding and tuning of the programs are usually done on the host computer and the programs are sent into the FPGA board. As software, the LabVIEW (Laboratory Virtual Instrument Engineering Workshop) by the same manufacturer is adopted. The LabVIEW is the graphical data-flow language, different from Fortran or C language which is written in sentences or characters. It is programmed by connecting many graphic components on the block diagram window as in an electric circuit chart, and the versatility of the LabVIEW enables the coding of the real-time phase controller. Another window on the PC, the front panel window, consists the human I/O's which handles the control and operation of the process and are displayed in graphics such as characters, numerical values, tables, switches, buttons and dials. The program on the block diagram is executed on the FPGA to interact with the front panel and the FPGA I/O's. Figure 4 shows the front panel and figure 5 shows a part of the block diagram of the control program.

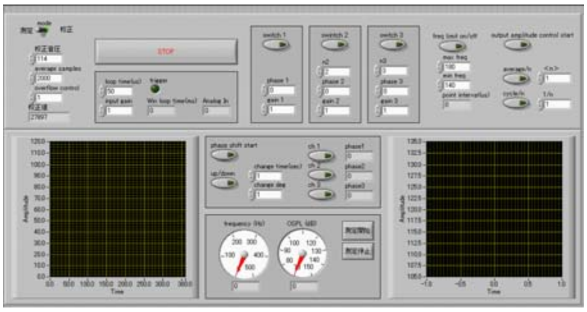


Fig. 4 Front panel of control program

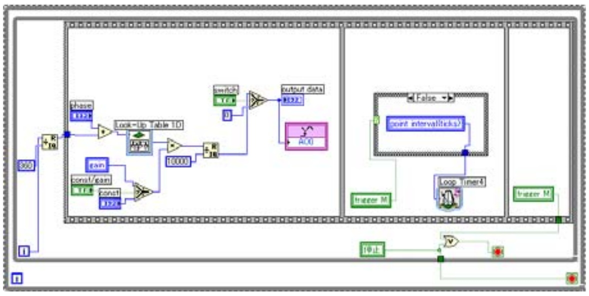


Fig. 5 Block diagram of control program

Measurement of the OASPL

In this study, the over-all sound pressure (OASPL) is to be measured. In the present setup, the OASPL is correlated to the microphone amplifier output voltage by

$$OASPL = A + 20\log_{10}\frac{<V>}{<Vc>},$$

where A is the reference OASPL, V_c is the microphone amplifier output voltage at the reference OASPL, and V is the measured microphone voltage. $< >$ denotes the average of root-mean square

$$<V> = \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_i^{\,2}}$$

where, N is the number of samples, V_i is the measured microphone-amplifier output voltage at every sampling timing. It is necessary to correlate $< V_c >$ at the reference OASPL before every experiments. The sound pressure level (SPL) is directly measured or calculated by the LabVIEW software.

Control method

The flame oscillation in the lean premixed burner has the peak preferential frequency and the OASPL is mainly attributed to this tone. From the observed pressure history, it is confirmed that the waveforms of the flame oscillation is approximately the sine waves with this peak frequency.

By taking advantage of these characteristics, in this study, the strategy to actively control the combustion oscillation is to reduce the oscillation at this preferential peak frequency by sine waves with this preferential frequency and the optimum phase. The control implementation is as follows:

- The trigger is set at the timing when the fluctuating pressure changes from negative to positive in every cycle.
- A time interval between the successive triggers is measured to calculate the preferential frequency. The frequency of the control sine waves is thus determined.
- The phase of the generated sine waves should be controlled to be optimum to reduce the oscillation. Arbitrary initial phase can be adopted at the timing of the trigger and the control sound waves are synthesized.

The phase of the control signal is kept at the optimum conditions by repeating this procedure over every cycle. In this study, the control system is implemented on the FPGA board and LabVIEW software by National Instruments.

Figure 6 shows more details of the present control strategy. In order to generate the control sine waves, the data of the sine waveform are preliminarily tabulated in 360 slices (1 data / 1 degree) on the FPGA board. This digitally tabulated waveform data is output sequentially synchronizing with the input. The time interval ΔT to hold the output is adjusted to the preferential frequency of the combustion oscillation calculated from the time interval of subsequent triggers. The starting phase at the trigger can be changed by displacing the read-in tabulated data. In this figure, i is the sequential clock counter, and j is the index of the tabulated waveform. At the time i, the waveform data $f(j)$, where $j = i + phase$, obtained from the tabulated look-up table are output Note that the difference between i and j is the phase difference. The loop resets and starts at the trigger timing when the acoustic input from the microphone changes its sign. The loop continues until the next trigger is input. Thus the generated waveform may not constitute complete one-period wave.

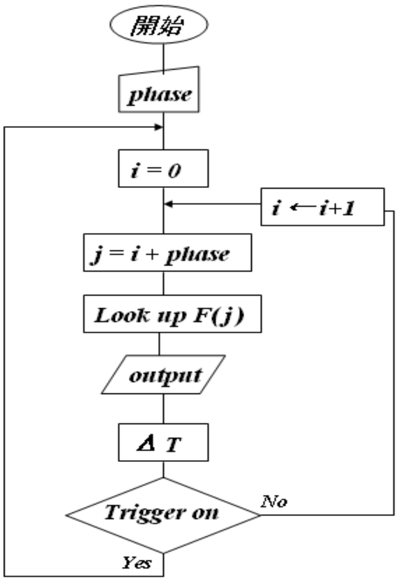


Fig. 6 Flowchart of generating phase shifted control signal

Merits of this strategy

The present control strategy has some merits in comparison with the conventional methods. Primarily, less data are necessary to control and reduce the combustion oscillation, so the control signal responds in real-time. Second, the identification of the second path is unnecessary. Third, the adjustment of the frequency and phase can be updated in every cycle. Finally, the phase-shift is adjusted directly, not in the form of tjhe time delay corresponds to the phase.

Experimental procedure and condition

The experiments are executed as follows: The first part is to seek the optimum phase and gain of the control signal to give rise to the minimum OASPL. By changing the phase of the control signal by 10 degrees, the initial optimum phase is obtained. After that, the gain is manually changed to obtain the optimum gain which give rise to the minimum OASPL. Finally, by changing the phase of the control signal from 0 to 360 degrees by 1 degree/second increase, the optimum phase is fine-tuned.

The second part is to investigate the details of the combustion oscillation with the control sound with the optimum phase and gain obtained earlier. The frequency characteristic of combustion oscillation is checked. The effectiveness of the control is to be confirmed. Also the waveforms of the combustion oscillation and the control signal are investigated.

The sampling frequencies for the control (D/A output) and for the measurement (A/D input) are 20 kHz and 2kHz, respectively.

Results and Discussion

OASPL and control signal phase

Figure 7 shows the OASPL - control signal phase relations. The control signal phase here is the phase difference between the input and output of the FPGA control board hardware. It is clearly seen that the OASPL changes definitely with change in control signal phase. The OASPL is reduced by 13dB as the maximum at the control signal phase of nearly 180 degrees. At this phase difference, the control sound is considered to generate the fluctuation that is nearly opposite to the primary combustion oscillation. Also it is observed that the OASPL may be increased, at the control signal phase nearly 0 degrees in the present configuration, and the control signal plays a detrimental role to enhance the coupling between the pressure fluctuation and heat release fluctuation. Note that the OASPL is in dB scale, so the interaction is observed to be non-linear.

Frequency characteristic with and without control

Figure 8 shows the frequency characteristics of the combustion oscillation with and without control. The phase difference between the combustion oscillation and control signal is fixed to the optimum phase of 186 degrees. It is confirmed that the sound pressure level at the peak frequency is reduced drastically as much as -20dB. The second peak at 310Hz disappears, and the sound level at the third peak, on the other hand, increases to become the second peak. The sound pressure increases slightly near the peak frequency, so the spill-over is observed. With control, the OASPL is decreased by -13dB to 118 dB, not so drastic at the peak sound level, but it is considerable amount, since the peak sound level is dominant in the OASPL.

Waveforms of oscillation

Figure 9 shows the pressure fluctuations of the combustion oscillation with and without control. The magnitude of the pressure fluctuation is about 65 Pa without control, and 18 Pa with control. In the actual experiment circumstance, the experimenters experienced clearly the low frequency noise reduction of the audible sound.

Figure 10 shows more details of the waveforms. The red and blue lines show the waveforms of the combustion oscillation with control, and the control signal, respectively. After starting at the no control condition, if the phase difference between the combustion oscillation and control signal is optimum, the amplitude of the combustion oscillation gradually decreases. When the control of the combustion oscillation is attained, the high frequency noise is outstanding. At this condition, the triggers are set at the false timing when they should not, and the sine control waves are not well formed, while the

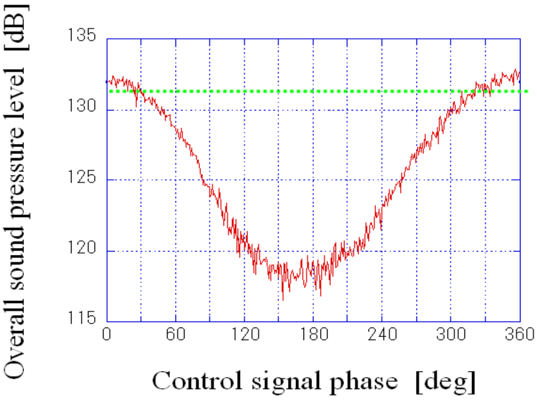


Fig. 7 Phase-OASPL relation

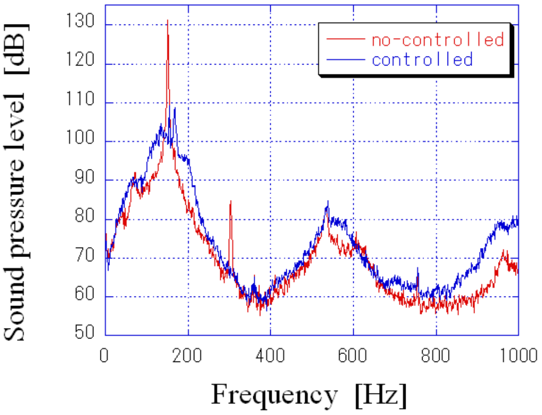


Fig. 8 Frequency characteristic of combustion oscillation with and without control

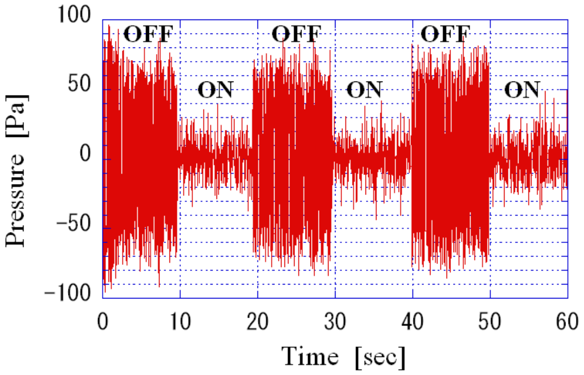


Fig. 9 Fluctuations with and without control

combustion oscillation with smaller amplitude and different nature appears. Since eliminating these noises is difficult due to the stochastic nature of the combustion, the amount of the reduction in the combustion oscillation seems to be near the limit due to the limitation inherent in the present type of control method. For further large reduction, some kinds of other control methods should be improvised, e.g., to control at the incipient oscillation phase.

Application to actual burners

At last, the feasibility of the present control strategy to the actual large-scale burners is to be discussed. There seems to be two main points which should be discussed here. One point is the frequency spectrum of the large-scale burner. The method implemented in this study is to reduce the oscillation of only one specific and preferential frequency identified by the system. After the authors' futile attempts, it was difficult to reduce more than two peaks at the same time. Therefore, possibility of application to actual machine depends on the frequency characteristics of its combustion oscillation. Ref. [7] gives the frequency characteristics of LM6000 gas turbine burners. It is confirmed that only one specific preferential peak exists at near 450Hz. So, it is highly probable that applying the control method implemented in this study to the actual large-scale burners.

Another point is the power of the actuators to be used for the control of the real large-scale burners. The output power of combustion rig used in this study is about 5kW and the OASPL at 130dB. In the actual large-scale burners, the power required by the actuators is larger by several orders of magnitude compared with the present experimental burner in linear scale. For this reason, using the loudspeaker as the actuator may not be possible. However, since large burners may have lower preferential frequency, so the mechanical fuel controller or the secondary fuel injection may be effective. Otherwise, again, totally different ways of active controls should be used, for, example, the control at the incipient phase, not in the limited cycle phase, when the oscillation is small.

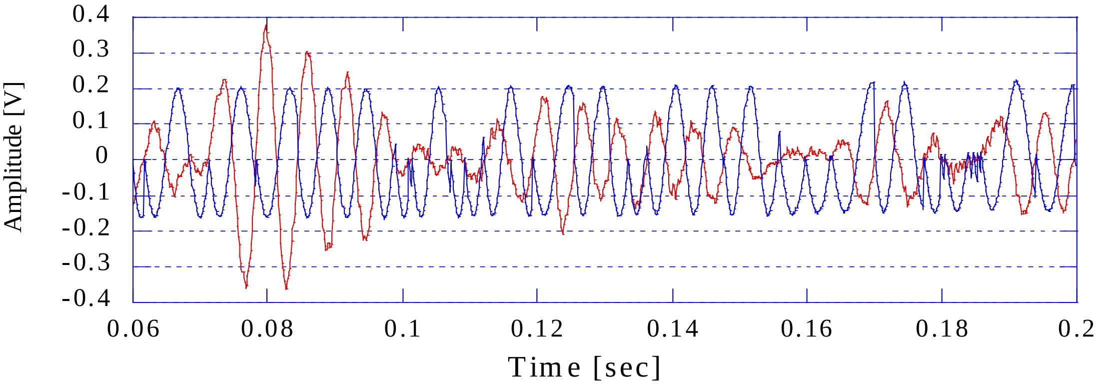


Fig. 10 Waveforms of control signal and flame with control

Conclusions

The active control method that makes use of the phase-controlled sound was established. The real-time controller was implemented in the present study, and the combustion noise reduction was achieved. The reduction was 20dB at peak frequency and 13dB in the OASPL.

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