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Sound Emission from Laminar Diffusion Flame with Controlled Oscillatory Fuel Flow

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ABSTRACT

The performance of an actuator for the active control systems to attenuate the pressure oscillation inside a combustor is investigated. This actuator is a valve using a piezo ceramics device (called a piezo-valve). It can oscillate flow rates of fuel at a specified frequency. Using this valve, a small laminar diffusion flame with varying heat-release is generated. The flame can emit sound with controlled amplitude and frequencies. This property will allow us to use the flame as the second sound source of which interaction with the pressure oscillation in the combustor is expected to attenuate the acoustic modes.

The paper provides characteristics of static and oscillating fuel flow rates of the piezo-valve against input voltages and frequencies as well as of sound emission from a small laminar diffusion flame with controlled oscillatory fuel flow rates. The sound emissions are amplified by the combustion, but the effect disappears above certain frequencies and is dependent on the fuel.

1. Introduction

Global environment protection is our great concern in recent years. Combustion technologies play a key role in the field, because the main source of the green house effect gases (CO_2) and air pollutants (e.g. NOx) come out of combustion.

In the field of gas turbines, the premixed combustion is usually adopted as a means of low environmental load combustion. This combustion method, however, often brings combustion instabilities that reduce the operation range of gas turbine. Among the unstable combustion phenomena, the combustion oscillation with intense pressure waves has practical significance, since this causes even structural damage of the combustion system.

The oscillatory instability occurs when the combustion process couples with the acoustic field of gas turbines in a way that excites natural acoustic modes in the system. The oscillation is generally driven by a feed-back type interaction between the flow and combustion process oscillation; acoustic energy supplied by an oscillatory combustion process excites one or more natural acoustic modes of the combustion system.

There are two approaches to avoid the combustion oscillation. One is a passive control approach and the other is an active control approach.

The former includes: modifications of combustion process by changing the fuel supply system to prevent the thermo-acoustic resonance, increase in the combustor's acoustic damping, and changing the acoustic properties of the combustor in order to change its natural acoustic modes frequencies away from frequencies where significant combustion process driving occurs. These passive solutions are, in some cases, practically used, while they are generally only applicable to a specific acoustic mode.

On the other hand, an active control approach is expected to be more flexible and to be more effective, particularly, for recent high performance combustors, in which many acoustic modes coexist (Hong, 2000, Candel, 2002).

An active control system may consist of a sensor that detects the instability, a controller that receives an output signal of the sensor and provides a control signal for an actuator, that attenuates the pressure oscillation inside a combustor. For example, a pressure transducer as a sensor, a control unit (e.g. a personal computer) with such a control algorithm, as "H∞", and a loud speaker as an actuator may compose a control system. The performance of the system depends on these components. In spite of many active solutions proposed, e.g. by control of a secondary flame inside a combustor, or by control of main fuel flow, still remain many problems to be solved for practical uses, because the performance complicatedly depends on the components.

In the context of an active control, we address the performance of an actuator that can vary the flow rate of the fuel for the secondary flame inside the combustor. This actuator is a valve using a piezo ceramics device (called a piezo-valve) and shows fast and quasi-linear responses to input signals. Using this valve, a small laminar diffusion flame with varying heat-release is generated. The flame can emit sound with controlled amplitude and frequencies like a speaker. This property will allow us to use the secondary flame as the second sound source of which interaction with the pressure oscillation in the combustor attenuates the acoustic modes.

2. Structure of Piezo-Valve

As a combustion control actuator, we choose a valve using piezo-celamics device (MV-112, Maxtek Inc., called "Piezo-Valve" hereafter). This valve is expected to change the flow rate in proportion to the control signal input, because of its fast response to the control signal.

The structure of the piezo-valve is shown in Fig.1. Diaphragm (made with piezo-ceramics) deforms by the applied voltage and changes the gap between the seat and the seal. The control signal generated by signal generator (WF1945, NF Corp.) is amplified by the bipolar power supply (HSA4011, NF Corp.) and is supplied to the piezo-ceramics diaphragm via lead wire and control the gap distance. The response of the valve gap to the applied voltage is quasi-linear within a certain input range. This means this valve can be expected to generate nearly sinusoidal oscillatory fuel flow rate, when the control signal is sinusoidal.

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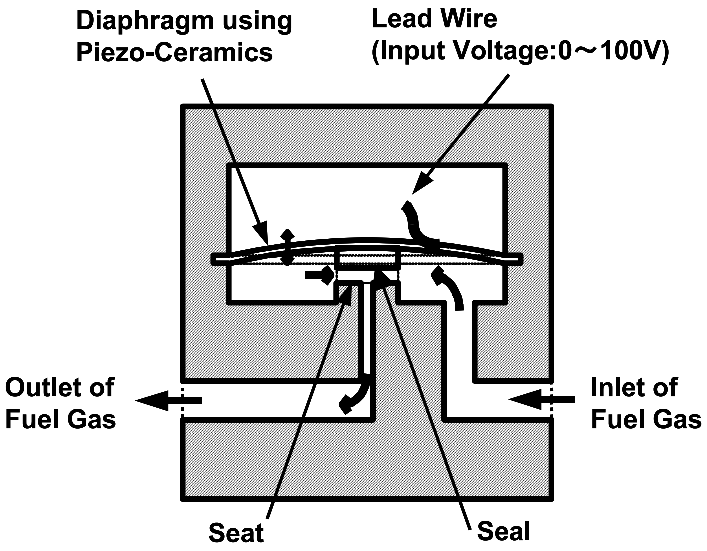

Fig.1 Structure of Piezo-Valve

3. Preliminary Experment

3-1. Sound Measurement Method

Fig.2 shows the schematic diagram of experimental apparatus. The fuel is supplied into the piezo-valve and goes through inside the valve and lead to a steel pipe with an inner diameter of 2mm and length of about 120mm connected at the outlet of the valve. The piezo-valve supplies the oscillatory fuel flow with both controlled amplitudes and frequencies from 60Hz to 1000Hz. At the end of the pipe, a fuel injection hole with diameter of 1mm is arranged. The oscillatory fuel flow injects into the open air from the hole, and an oscillatory diffusion flame is kept. As a fuel, hydrogen and methane are used. Reynolds number based on the diameter of the fuel injection hole and mean injection velocity of the fuel is between 100 and 1000.

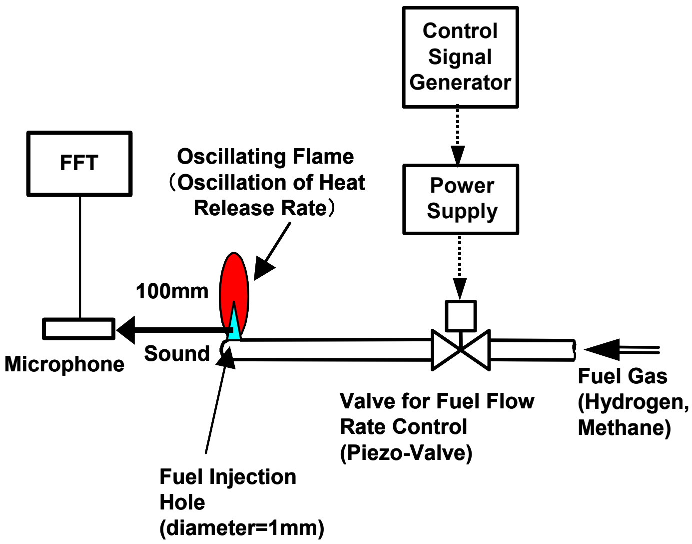

Fig.2 Experimental Scheme of Sound Measurement

Fuel is supplied at the constant pressure (0.2MPa) at the valve inlet and choked at the valve throat. This means that flow rate is proportional to the gap between seat and seal. Consequently sinusoidal input signal for the control of gap causes the oscillating flow rate. This oscillating flow generates the sound by itself. In addition to that, when this oscillating fuel is burned as the diffusion flame, it generates the oscillatory heat release that generates the pressure oscillation (i.e. sound). This sound generation by combustion is expected to amplify the sound pressure level.

In experiments, both the sound from the oscillatory fuel flow itself (without flame) and that from the oscillatory heat release by the oscillating flame (with flame) are measured by the microphone of the sound level meter (NL-14, RION Co. Ltd.) in the open air. The microphone is placed in the horizontal plane where the fuel injection hole exists and at 0.1m apart from the fuel injection hole. Obtained data is analyzed by the spectrum analyzer (R9211B, Advantest).

The characteristics of sound emission from the oscillatory diffusion flame are investigated through a series of experiments.

3-2. Directivity of Sound generated by Piezo-Valve

To confirm the influence of the measurement position (i.e. position of the microphone), directivity of the sound emitted from piezo-valve is investigated.

In Fig.3, the sound level data obtained at the several points on the circumference with radius of 0.1m and of which center is fuel injection hole are shown. In this case, fuel is hydrogen and burned. Frequency of control signal applied to the valve is 200Hz. A sound level meter has a flat frequency response and the background noise is corrected in shown data.

Obtained sound pressure levels hardly depend on the measurement position. This indicates that sound from such a small flame used in this study does not show the directivity and the flame can be regarded approximately as the monopole sound source. The measurement result of the sound generated from the non-burned oscillatory fuel flow (without-flame case) indicates that the sound also has no directivity. With these results, we fixed the measurement position at the point 0.1m apart from the fuel injection hole and at an angle of 90 degree with the direction of fuel injection.

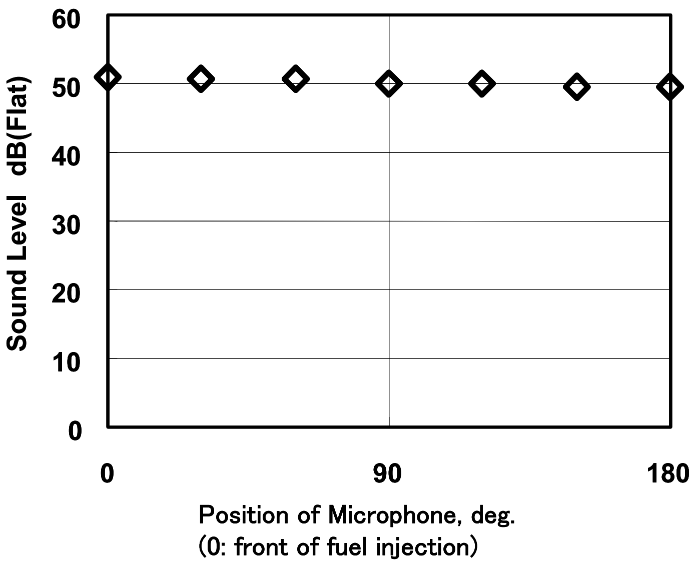

Fig.3 Directivity of Sound from Flame

4. Flow Rate Controlled by Piezo-Valve

4-1. Static Flow Rate Measurement

Before the measurement of the sound emission from the oscillatory flame, we confirmed that the flow rate of the fuel could be controlled by the piezo-valve.

First, static relation between control signal and flow rate is measured. Fig. 4 shows the relation between control signal voltage and static flow rate. Fuel is hydrogen. The expression "static flow rate" is due to the piezo-valve's creep. After the change of the voltage of the input signal is complete, piezo-elemnt shows a slow creep. This means that flow rate continues to increase slightly after its step-wise increase caused by the step-wise increase of control signal voltage. Therefore, in Fig. 4, the data obtained after the flow rate reaches the steady value are plotted. Measurement of flow rate is made by the film flow meter (SF-101, STEC inc.) and by the dry test gas meter (DC-2, Shinagawa Corp.). From this figure, it appears that the response linearity of the valve is lost in the low voltage region. It implies that when piezo-valve is used as the actuator with the quasi-linear response, control signal must be biased to the extent that the input voltage is in the quasi-linear region.

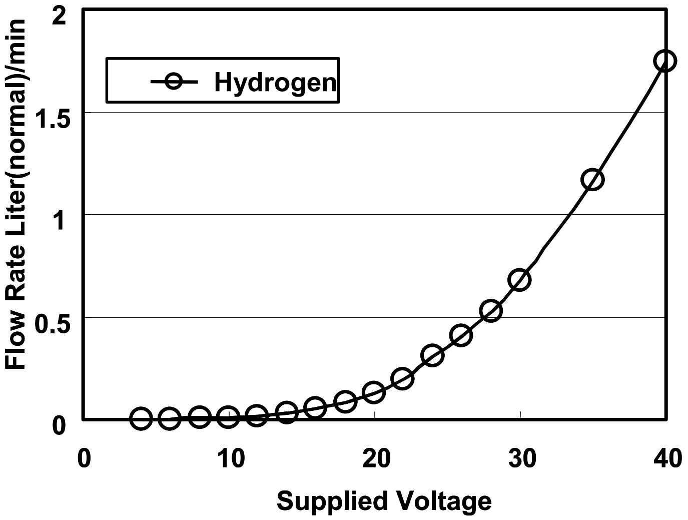

Fig.4 Relation between Static Flow Rate and Input Voltage

4-2. Oscillating Flow Rate Measurement

1) Measurement Method. The role of piezo-valve as an actuator for the combustion control is to generate oscillatory flow rate. Dynamic relation between control signal and flow rate is, therefore, measured to confirm that the valve oscillates the flow rate as expected. Fig. 5 shows the experimental scheme to measure the flow rate oscillation. In this experiment, flow injection hole is covered with small space with volume of 11.4cm^3. The flow rate oscillation is indirectly measured from the pressure change inside the space. Pressure measurement is made by 1/8 inches condenser microphone (#4138, Bruel & Kjaere). Here, it is checked that there is no resonance mode due to the geometry of the space and its volume. Because measured data shows the almost sinusoidal pressure change with time, we assume that flow rate also oscillates sinusoidally. Then, the flow rate is estimated from the time derivative of pressure change, using the mass conservation and state equation of ideal gas.

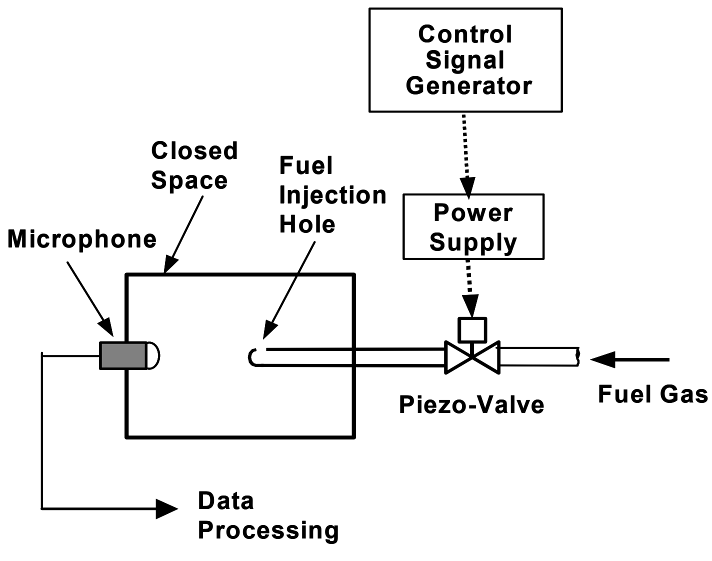

Fig.5 Experimental Scheme of Flow Rate Measurement

2) Experimental Result of Oscillating Flow Rate. Fig. 6 shows the measurement result of flow rate oscillation. Input signal is pre-energized to voltage of 30V to use the quasi-linear response region of the valve. Amplitude ranges are from -12V to +12V and from -8V to +8V. It is observed that the larger amplitude of input signal is, the larger the flow rate oscillation. On the other hand, even if the input voltage is the same, obtained flow rate oscillation differs with the difference of the input signal frequency. As the control actuator, the one with simpler response is preferable for the simplification and the stability of the control system. The characteristics of piezo-valve's response shown here implies, however, that robust control system with this valve will require robust control algorithms, precise database of valve response, and so on.

Obtained amplitude of the flow rate oscillation in Fig. 6 is smaller than that is expected from Fig. 4 (relation between control signal and static flow rate). This tendency may be caused by the creep of piezo-valve. On the other hand, larger amplitude of the flow rate oscillation is observed in the higher frequency region. This can not be explained only by the creep.

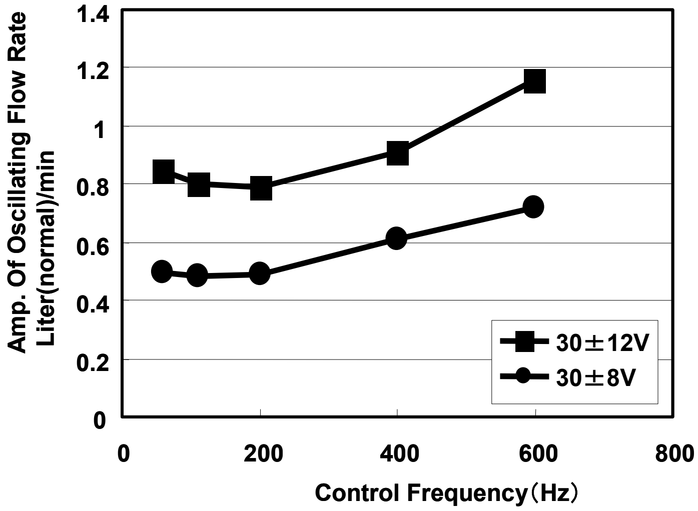

Fig.6 Amplitude of Flow Rate Oscillation

3) Confirmation of Result of Oscillating Flow Rate. Amplitude of the oscillating flow rate is estimated by the measurement of pressure oscillation inside the small space. To confirm that flow rate oscillation data are not affected by the space, sound level measured in the open space is compared to that theoretically derived from the experimentally estimated flow rate oscillation. Sound level is measured as shown in Fig. 2 (as described in Section 3-1, i.e. small space covering the fuel injection hole in Fig. 5 is separated). Fig. 3 tells that the sound source in this study shows no clear directivity and can be taken for monopole sound source. Theoretically, Sound Level (or Sound Pressure Level; SPL, dB) emitted from the oscillating sphere is expressed by following equation (Yoshikawa and Fujita, 2002).

$$SPL = 20\log_{10}\left[\frac{\rho_0 Q_0 f}{2\sqrt{2}r} \Big/ 2\times10^{-5}\right] \tag{1}$$

SPL is Sound Pressure Level (dB), Q_0 is the amplitude of the oscillating fuel flow rate (m^3/sec), f is frequency (Hz), r is distance from sound source to microphone (m), ρ_0 is ambient air density (kg/m^3), and 2×10^{-5} is reference pressure (Pa), respectively. When f of right hand side of this equation is transposed to left hand side, right hand side becomes independent of the frequency as expressed by Eq. (2).

$$SPL - 20\log_{10} f = 20\log_{10}\left[\frac{\rho_0 Q_0}{2\sqrt{2}r} \Big/ 2\times10^{-5}\right] \tag{2}$$

In Fig. 7, experimental results are plotted with the theoretical line expressed by Eq. (2). Experiments are carried out in 4 cases of amplitude of input signal. Especially, as for the case of amplitude of 16V, pre-applied voltage is 16V to avoid the non-linear response region shown in Fig. 4. In each case, experimental data agree with the theoretical line fairly well.

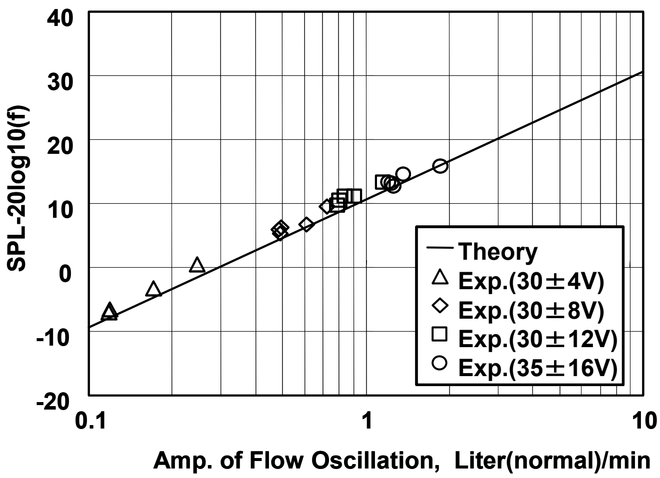

Fig. 7 Comparison between Experiment and Theory for Flow Rate Oscillation

5. Combustion Sound Measurement

5-1. Influence of Combustion on Sound Emission

To clarify the contribution of combustion to the rise of SPL, sound from fuel injection without combustion is compared to that with combustion. In every experiment, input signal imposed on the piezo-valve is sinusoidal wave with amplitude of 8V around the voltage shift of 30V for every frequency. Sound level is measured in the open space as shown in Fig. 2. In every measurement, a sound level meter has a flat frequency response.

Fig. 8(a), (b) are the spectrum profile in the case of control frequency of 150Hz. In this figure, the background noise in the experimental data is not corrected. Fig. 8(a) is the result of without-combustion case and (b) is that of with-combustion case. Sound level meter has a flat frequency response and the background noise is NOT corrected. In both figures, clearly distinguishable peak can be seen at the control frequency (150Hz). In addition to that, its higher harmonics are also observed. The peaks at the control frequency and of higher harmonics are higher in with-combustion case than in without-combustion case. Combustion enlarges the sound emitted from the oscillatory fuel flow, while background noise is not influenced by the combustion. The fact that the only sound at control frequency and its higher harmonics are magnified proves that heat release oscillation by the oscillating flow rate causes this augmentation in sound level.

Fig. 9 shows the change in sound level by combustion. In the experimental data shown hereafter, the background noise is corrected. Hydrogen is used as a fuel. In the figure, triangle marks are sound level in the case of no fuel flow (only diaphgram is vibrating. flow rate=0). This is the sound level of valve itself. From this plot, it is clear that sound generation by the valve itself is negligible compared to that by flow rate oscillation or that by oscillating flame. The data of without-flame increase linearly in this figure, this trend is consistent with the sound generation given by monopole sound source theory. In lower frequency region, the sound level of with-flame indicated by circle is about 20dB higher than that of without-flame. This sound increase effect seems, however, diminish in higher frequency region.

In Fig. 10, difference in sound level between the without-flame case and the with-flame case is shown. Zero value of vertical axis indicates that increase of the sound by combustion is not be observed. Positive and negative values show the increase and the decrease of sound by combustion, respectively. In this figure, augmentation of sound by combustion is larger in lower frequency region as shown in Fig.9. In higher frequency region the augmentation disappears. The sound generation of burning and oscillating fuel flow is considered that the superposition of the sound from fuel flow oscillation and that from heat release oscillation by combustion of oscillating fuel flow. Thus smaller augmentation and drop of sound level by combustion in higher frequency region is likely due to a phase discrepancy between sound from fuel oscillation and that from heat release oscillation. And furthermore, it may be due to the decrease of amplitudes of heat release rates.

Sound emission from the oscillation of fuel flow is enhanced by the combustion, whereas this enhancement effect is diminished as valve control frequency becomes higher.

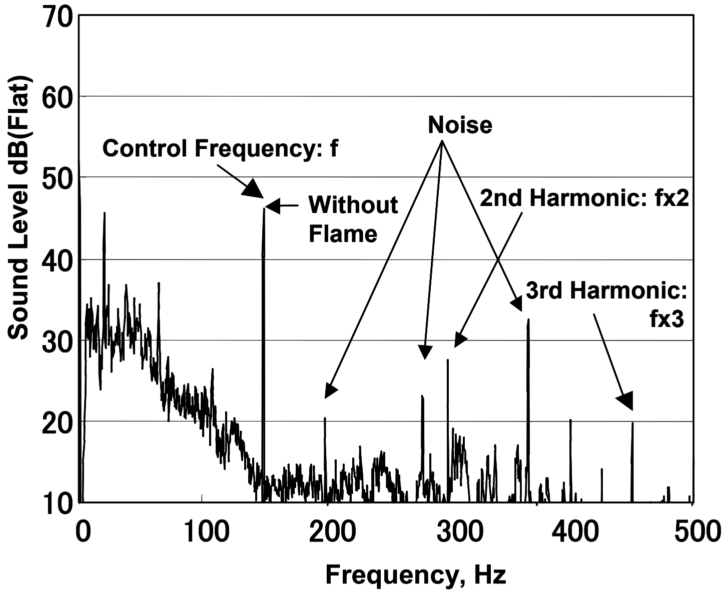

Fig. 8(a) Spectrum of Sound Emitted by Oscillating Fuel Flow

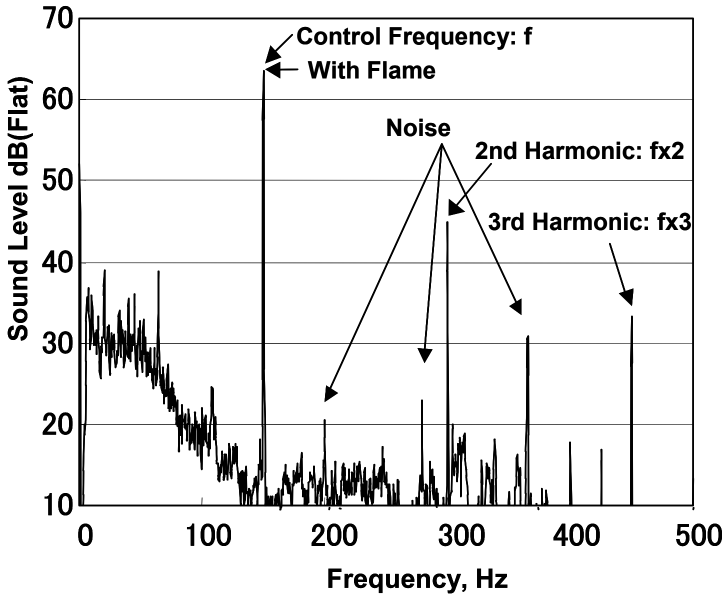

Fig. 8(b) Spectrum of Sound Emitted by Oscillating Flame

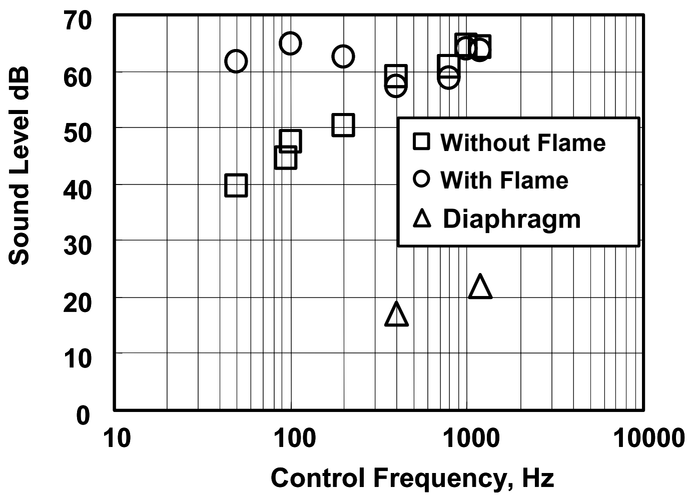

Fig. 9 Sound Level and Control Frequency

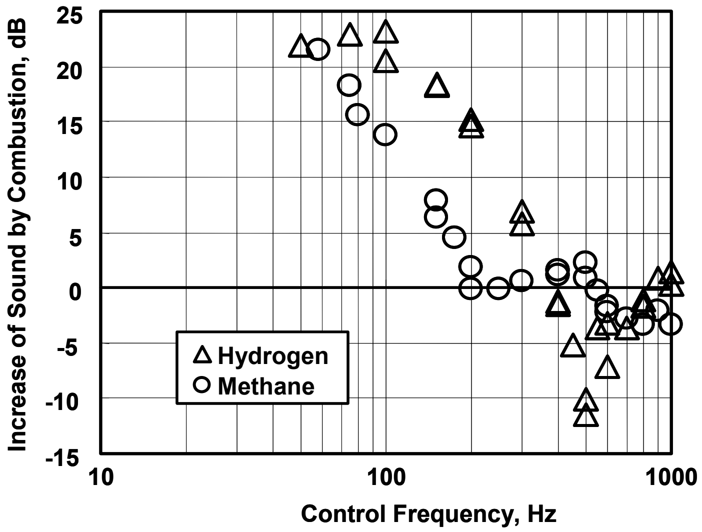

Fig. 10 Sound Increase by Combustion

5-2. Influence of Fuel on Sound Emission

Magnitude of sound enhancement effect by combustion seems to depend on the phase gap between sounds from unburned oscillating fuel flow and from oscillating heat release by combustion. This phase gap appears to be dependent upon the combustion process. To be more precise, in combustion process, ignition delay, burning velocity, and so on, seem to dominate the response speed of flame. Because of these factors, flame cannot respond to the change of fuel flow rate in case where the control frequency is relatively high. Hence sound enhancement effect by combustion seems to depend on the fuel.

To investigate these effects of combustion sound, experiments are carried out using methane as a fuel, which has different combustion characteristics from hydrogen, such as ignition delay and reaction rate.

Fig. 10 shows sound level difference between the without-flame case and the with-flame case with reference to methane combustion. In comparison with hydrogen combustion, sound increase effect by methane combustion diminishes at lower frequency. This is likely caused by slower combustion process of methane that causes the larger phase gap. To improve the combustion response speed, hydrogen is added to methane. This is expected to improve ignition delay.

Fig. 11 shows the experimental results for the mixed fuels. Both pure methane and mixture of methane and hydrogen show no difference in sound increase effect, unlike our expectation. As for pure methane, it is observed that flame is slightly lifted from the fuel injection hole. On the other hand, addition of hydrogen ameliorates the ignition property and makes flame held at the injection hole without lift. From these observations, it can be mentioned that the improvement of ignition shows only effect on the large scale property of flame (for example, flame shape) and have no effect on the response of combustion to the fuel flow oscillation. This appears that the response of the diffusion flame to the flow rate oscillation is dominated by diffusion process in the flame. In other words, the time scale of diffusion determines the flame dynamics and worse diffusivity of methane is not improved by addition of hydrogen.

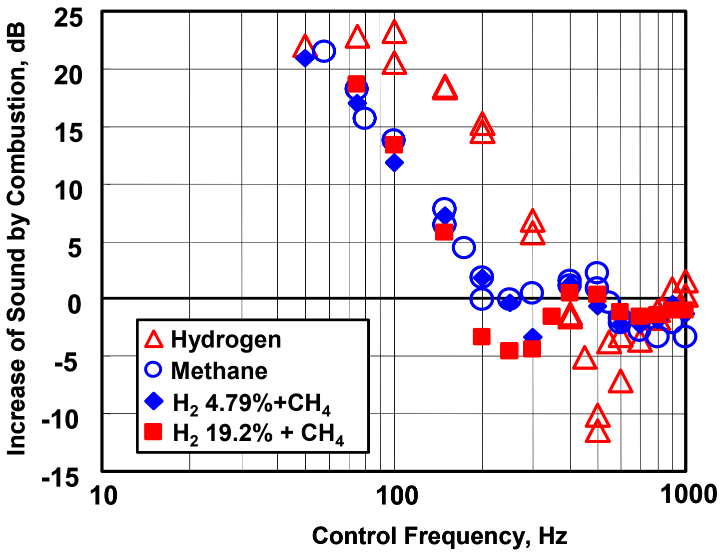

Fig. 11 Sound Increase Effect by Various Fuels

5-3. Phase Shift of Sound Emission

Above results suggests that phase delay of sound emission from the flame is important in sound enhancement effect of combustion. The phase difference between the sound emission and the control signal is measured as for both with-combustion and without-combustion cases.

Fig. 12 shows the measurement results of phase shift from the control signal. Fuel is hydrogen. In the low frequency region, phase advance can be seen. This advance is due to the fact that piezo-valve acts like a condenser and the valve opening is nearly proportional to its charge which is proportional to the input voltage. On the other hand, the fuel flow rate is proportional to the valve opening and the sound pressure signals are proportional to the derivative of fuel flow rate. Hence, in the case of sinusoidal input voltage signal, the phase of the sound pressure advances at 90 degree against that of the signal.

Both sound from the oscillatory fuel flow and that from the flame show the phase shift from the control signal and its magnitude becomes larger as the signal frequency becomes higher. The phase shift of sound emitted by the oscillatory fuel flow is likely due to the fluid mechanical delay. On the other hand, the phase shift of sound by combustion is larger than that from the oscillatory fuel flow in lower frequency region. This seems due to the delay caused by the slow diffusion of fuel as mentioned in foregoing section.

Here, we note that the sound observed in the with-flame case is superposition of sound from the oscillatory fuel flow and that from the oscillatory combustion. When the sound from the oscillatory fuel flow and that from the oscillatory combustion are given by expressions (3) and (4) respectively,

$$A \sin \theta \quad (3)$$

$$B \sin (\theta - T) \quad (4)$$

superposition of both sounds is expressed as following.

$$K \sin\left(\theta - D\right) \quad (5)$$

Here,

$$K = \sqrt{\left(A + B\cos T\right)^2 + B^2}\ ,\ \tan D = \frac{B\sin T}{A + B\cos T} \quad (6)$$

and delay in sound from the oscillatory fuel flow is neglected. In ex.(4), T is real phase delay of sound by the oscillatory combustion from that by the oscillatory fuel flow. However, observed phase delay in experiments is approximately expressed by D in ex.(5). When A is much larger than B (combustion shows no contribution to the sound enhancement), from ex.(6), tan D is nearly equal to 0. Then D is 0, even if T has a certain value. This agrees with the experimental result shown in Fig. 12. In other words, as mentioned in section 5-1, the amplitude of oscillatory heat release rate decreases in higher frequency region

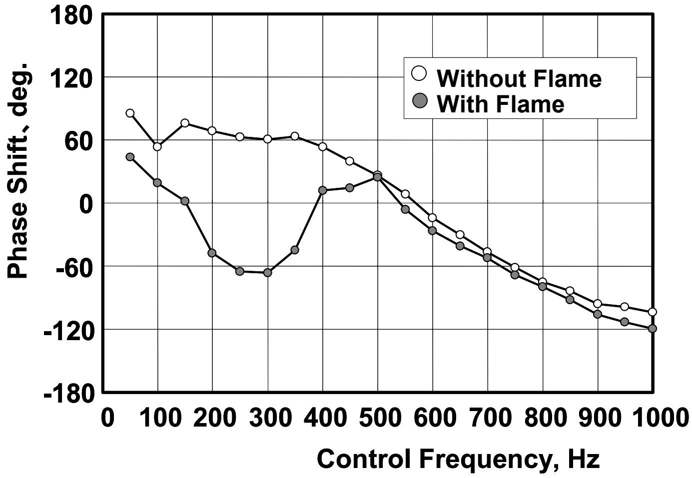

Fig. 12 Phase Shift from Input Control Signal

5-4. Sound Emission from Multi-Hole Fuel Injection

Sound pressure level obtained by a piezo-valve in above experiments seems to be not enough for the suppression of combustion noise or combustion oscillation in the combustor. For the combustion sound suppression, amplification of the sound emission from the oscillating fuel flow will be required. Multi-hole fuel injection system with actuators that can generate the fuel flow oscillation is expected to achieve this. In such system, interaction between each flame may influence the sound generation. Hence influence of positions of fuel injection holes on the sound generation is investigated.

As shown in Fig. 13, influence on the combustion sound emission of fuel injection holes arrangement are investigated as for two cases: A) Fuel injection holes are set at the axisymmetric position facing in the opposite direction. B) Fuel injection holes are arranged in a line facing in the same direction.

Fig. 14 shows the influence of holes arrangement on the sound enhancement effect by combustion. Fuel is hydrogen. In the figure, black circle indicates the result for the single-hole case. For type B arrangement, distance between holes influences the sound enhancement effect. In the case of shorter distance (1.5mm and 5mm), sound increase by combustion is smaller than the single-hole case. On the other hand, in the case of holes with distance of 10mm facing in the same direction (type B) and holes facing the opposite direction (type A), the sound enhancement effect is almost same as in the single-hole case. This appears that, in the case that the distance between fuel injection holes is short, the local oxygen concentration in the neighborhood of each flame becomes smaller and this causes the worse response of flame. To avoid this undesirable interaction between flames and maintain the sound emission from each flame at the same level, optimization of arrangement of fuel injection holes and air supply mechanism are required.

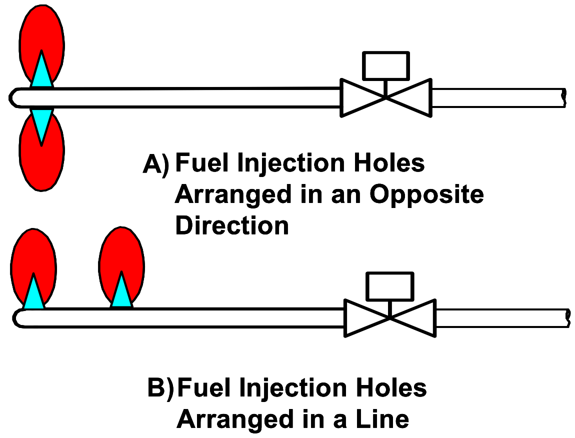

Fig. 13 Fuel Injection Holes Arrangement

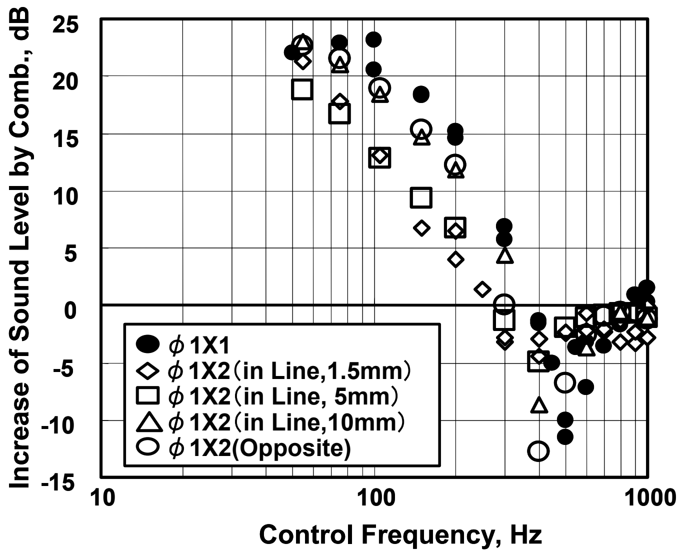

Fig. 14 Influence of Injection Holes Arrangement

6. Conclusions

1) The valve can vary the flow rate in quasi-proportion to the input voltage.
2) Both the oscillatory fuel jet and the flame can be regarded as a monopole sound source.
3) The combustion amplifies the sound emission. But this effect disappears above a certain frequency.
4) The increase in the sound pressure level by the combustion and the frequency at which the amplification effect is lost depend on the fuel.

Acknowledgement

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References

Hong, B-S., Yang, V., and Ray, A., 2000, "Robust Feedback Control of Combustion Instability with Modeling Uncertainty", *Combustion and Flame*, Vol.120, pp.91-106

Candel, S., 2002, "Combustion Dynamics and Control: Progress and Challenges", Hottel Lecture, *29th International Symposium on Combustion*, July 20-26

Yoshikawa, S. and Fujita, H., 2002, "*Basic Acoustics*" (in Japanese), Kodansha Ltd. , Tokyo, JAPAN