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Application of the Helmholtz Resonator for Reducing the Combustion Oscillation in a Gas Turbine

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ABSTRACT

Use of the lean premix combustion for gas turbines is promoting recently. Unfortunately, this style of combustor is prone to the combustion oscillations which tend to affect the reliability of the combustor.

The combustor which adapts the premix combustion has been tested under atmospheric pressure conditions. The combustion flames are visualized by using the photodiode and the high speed video camera to study the relations between the flame motions and the dynamic pressures. From these results, it is found that there are close relations between the flame motions and the dynamic pressures.

Helmholtz resonators are applied for reducing the combustion oscillations. It is found that the dominant combustion oscillations can be reduced by optimizing the size of resonator parameters. And, interesting observations for dynamic pressures in both the combustion tube and the resonator are presented in this paper.

The controlling system, which automatically controls the resonator volume to minimize the amplitude of combustion oscillations based on the dynamic pressure signal in the combustion chamber, is applied to the combustor. The test results show that the controlling system can achieve large reduction of the combustion oscillation in the wide range of operating conditions.

NOMENCLATURE

C: speed of sound
L: length of resonator
L1: length of resonator 1
L2: length of resonator 2
Ls: length of resonator throat
Pm: premix ratio
S: cross sectional area of resonator throat
Tad: adiabatic combustion temperature
U: gas velocity at swirler outlet
V: volume of resonaqtor
Δp: dynamic pressure

INTRODUCTION

There is a possibility of combustion oscillation whenever combustion takes place within a combustion tube. Recently, the design principles of gas turbine combustors have changed completely. In stead of the diffusion-style combustion, the lean premix combustion is now accepted as a standard approach to reduce NOx emissions. In the lean premix combustion, fuel and air are mixed upstream of the combustion zone to avoid the local high temperatures that are known as major cause to produce thermal NOx. Although the lean premix combustion is an attractive combustion method for reducing the NOx emissions, this method of combustion has been accompanied by combustion oscillations occasionally.

Combustion oscillations occur when minor variations in the air/fuel ratio or mixing processes lead to significant change of the heat release rate, and the combustor`s acoustic resonance may result in large oscillations. Combustion oscillations must be eliminated in a final combustor stage of the combustor development because the combustor lifetime may be shorten by the combustion oscillations.

There are extensive literatures on the combustion oscillations in the combustors. Rayleigh first explained the so-called “singing flame” phenomenon over 100 years ago(Rayleigh, 1896). Putnum has presented an overview of combustion oscillations (Putnam, 1971). Keller points out that the operation near the lean limit is especially prone to the oscillation problems (Keller, 1995). Nowadays, studies of the lean premix combustion oscillations have been reported with regard to gas turbine operating conditions(for example; Douglas et al. 2001,Anson et al., 2002). In practice, the task of studying combustion oscillation in a gas turbine is complicated by the specific acoustic response of a given combustor design. Thus, no general trends have been proposed to describe the effect of usual gas turbine operating parameters such as inlet air temperature, pressure and equivalence ratio. Consequently, tests of proposed oscillation remedies are complicated because it is difficult to specify an appropriate test matrix.

In reducing the combustion oscillation, fuel and air modulations have been employed to control the instabilities which concern the combustion oscillations(McManus et al. 1991; Annaswamy et al. 1995; Paschereit et al. 1998). The complexity of the combustion process and the lack of suitable actuators make active control of combustion instabilities a challenging problem. Lang et al. have presented results based on the study of a longitudinal combustion instability mode and its active control at one operating condition in a small scale premixed combustor using loudspeaker-based actuation(Lang et al.;1987). Although the resonator is known as effective methods for reducing the combustion oscillation, there are few literatures about application of resonator in gas turbines. Recently, the literatures can be seen(for example; Belluccl et al, 2001)). However, many of them are dealing with models and analyses .

Authors have reported the relations between the combustion oscillations and test conditions such as swirl strength by using the combustor which simulated the can type gas turbine combustor (Yamanaka et al. 1999). Then, the resonator was applied to reduce the combustion oscillations in the combustor. The experimental data showed that the resonator was useful to reduce the combustion oscillation in the gas turbine combustor(Yamanaka et al. 2000). To

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design the optimum resonator, the size of resonator was evaluated (Yamanaka et al. 2002).

In this work, flame pictures and intensities of flame lights were taken to study the relations between flame behaviors and combustion oscillations at first. Then, the dynamic pressures in both the combustion tube and the resonator were measured to study the performance of the resonator. Finally, the controlling system which automatically controls the resonator volume was tested. In this paper, these test results will be presented and discussed.

EXPERIMENTAL DESCRIPTION

Test combustor

All of the tests discussed in this studies are performed with a single burner and a water cooled combustion tube. A cutaway view of the experimental combustor is shown in Figure 1.

A pilot fuel nozzle, which has eight holes of 1.2mm diameter, is set at the center of the burner. A swirler, which has the swirl strength of 0.35, is used to stable the combustion flame. Air or premixed gas is supplied to the combustion tube through the swirler.

Inner diameter of the combustion tube is 224mm. The orifice, which is simulated the turbine nozzles of the gas turbine combustor, is set at the position of 1500mm from the inlet of combustion tube. In this test ,the orifice plate, which has 23% open area to the cross sectional area of combustion tube, is used.

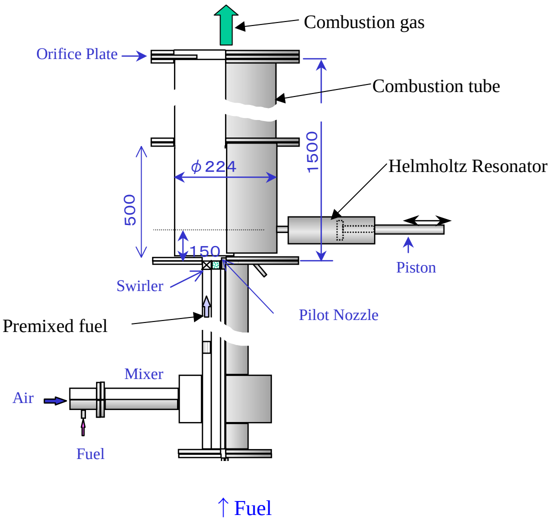

Figure 1 Configuration of experimental combustor

Resonators are applied to reduce the combustion oscillations. Figure 2 shows the configuration of the resonator. The resonator consists of a cavity with a throat.

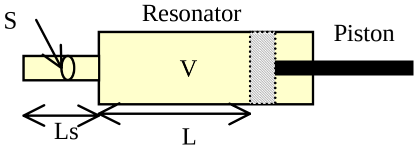

Figure2. Key parameters of resonator

The resonance frequency ,f, is give by

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{LsV}} \qquad (1)$$

Where, c is a speed of sound in the throat, S is a cross sectional area of the throat. Ls is a length of the throat and V is a volume of the resonator.

It is necessary to understand the dominant frequencies of the combustion oscillations(dynamic pressures) and the pressure modes along with the axial length of combustion tube before designing the resonator. These test results obtained by using this combustor have been already reported(Yamanaka et al. 2000).

According to the equation (1), there are three parameters(S, Ls, V) to optimize the resonator. However, the optimum size of the resonator will change with the test conditions such as combustion temperature and pressure. Therefore, the S and the Ls are fixed , and the V is controlled by moving the piston (see Fig. 2). On the other hand, there are limits for the S and the Ls to reduce the combustion oscillation(Yamanaka et al. 2002). Then, the sizes of resonator are chosen as follows.

Throat diameter : 25.4mm
Throat length(Ls) : 55.5mm
Resonator diameter : 105mm
Resonator length (L) : from 0mm to 800mm

According to the test results of the pressure modes measurements in this combustor, the amplitudes of dynamic pressures are the largest at the end of combustion tube(Yamanaka et al 2000). Therefore, the resonator is set near the inlet of combustion tube which is 150mm downstream from the inlet of combustion tube.

Quartz glass tube of 224mm diameter(500mm length) is mounted at the upstream of combustion zone in stead of the metal tube to study the relations between the dynamic pressures and the flame behaviors. In this case, the resonator is set at the bottom of the combustion tube.

Instrumentation

The schematic diagram of instrumentation is shown in Figure 3. Piezoelectric sensors are mounted along the combustion tube wall to measure the dynamic pressures. The signals of dynamic pressures are recorded by the data recorder, and the frequency spectrums and the amplitudes of dynamic pressures are analyzed by the FFT analyzer.

A photodiode and a high speed video camera are mounted near the quartz glass combustion tube to evaluate relations between flame behaviors and dynamic pressures. According to the image processing method, the evaluation of flame behaviors requires flame pictures which are 10 times as large as flame behaviors. As the dominant frequency is about 300Hz at most, the flame pictures are taken with 4500 frames per second, and the pictures are recorded by a video recorder. The signals of photodiode, which show the intensities of the flame lights are recorded by the data recorder. These data are used to analyze the relations between flame behaviors and dynamic pressures by using the image processing method.

Figure 4 shows the measurement points of dynamic pressures.

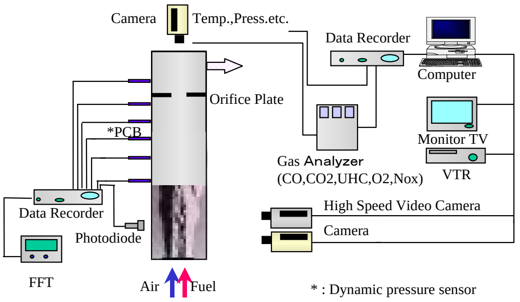

Figure3. Schematic diagram of instrumentation

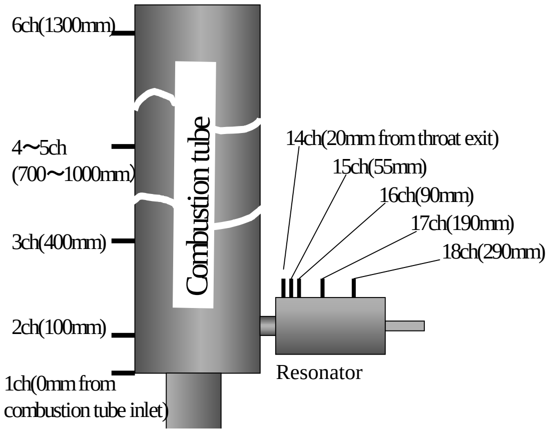

Figure 4 Measurement points of dynamic pressures

Test conditions

Test conditions are as follows.

Fuel : City gas 13A
Pressure : Atmospheric pressure
Inlet air temperature : Room temperature(around 30℃)
Gas velocity at swirler outlet(U) : 50 – 85m/s
Adiabatic combustion temp.(Tad) : 1600℃
Premix ratio(Pm) : 0 – 100%

Composition of the city gas 13A is as follows(Vol.%)

. CH_4; 88.5
C_2H_6; 4.6
C_3H_8; 5.4
C_4H_{10}; 1.5

RESULTS AND DISCUSSIONS

According to our previous report, there are two dominant frequencies in the test combustor (Yamanaka et al. 2000). One is around the 70Hz which has an even dynamic pressure through the combustion tube. The other is around the 270Hz which has the pressure mode. The pressure mode is that pressure loops are found at the ends of combustion tube and the pressure nod is found at the center of combustion tube. From these modes, it is found that the 70Hz is a Helmholtz type oscillation, and the 270Hz is an acoustic type oscillation.

Flame behaviors

Figure 5 shows the signals of the photodiode and the dynamic pressures when the dynamic pressures are relatively large. The intensities of flame light and the dynamic pressure fluctuate with the same phase difference. Figure 5 also shows the frequency spectrums as a function of frequencies from sampled time data. The dominant frequencies are the same(270Hz) for both dynamic pressure and photodiode.

Figure 6 shows the signals of the photodiode, the dynamic pressures and the frequency spectrums when the resonator is applied to reduce the dynamic pressures at the same conditions as those of Figure 5. The fluctuations of the intensity of flame light as well as the dynamic pressure fluctuations are small. There are no dominant frequencies in this condition.

From these results, it is found that there are close relations between the intensity of flame lights and the dynamic pressures.

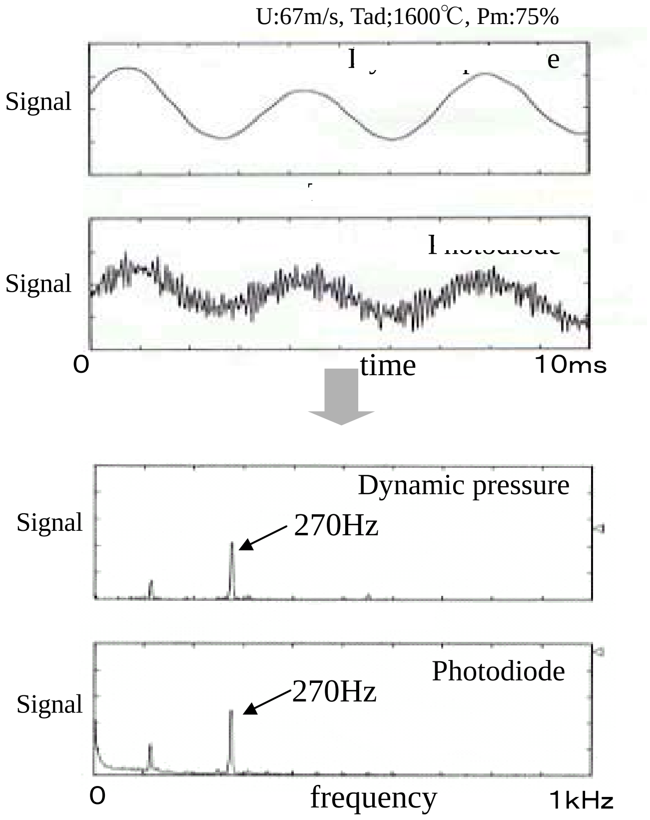

Figure 5 Signals of the dynamic pressure , photodiode and frequency spectrums when the dynamic pressures are large

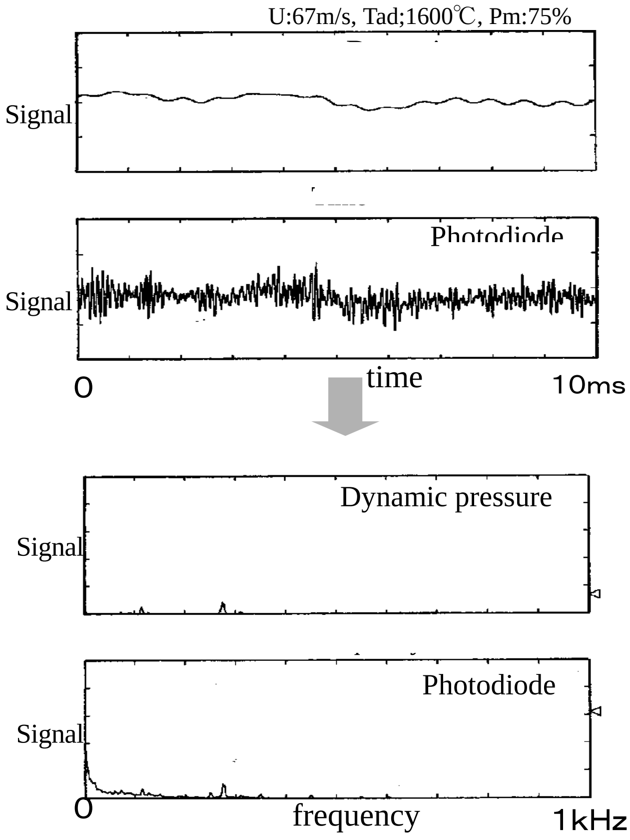

Figure 6 Signals of the dynamic pressures, photodiode and frequency spectrums when the dynamic pressures are small

Figure 7 shows the examples of instantaneous flame pictures which are taken by the high speed video camera(4500 frames per second). By arranging these flame pictures in order, it is found that flame configurations are changing periodically. Therefore, an image processing method is applied to investigate the relation between the flame behaviors and the dynamic pressures. Figure 8 shows an example of flame configuration with three steps intensities of the lights which are obtained from the image processing method. Although there are many parameters of deciding the flame configuration, the area of flame is chosen to investigate the relation between the flame behaviors and the dynamic pressures in here.

Figure 9 presents the fluctuations of the flame area and the dynamic pressure where the dynamic pressure is relatively large. The flame areas and the dynamic pressures are fluctuating with the exactly same period.

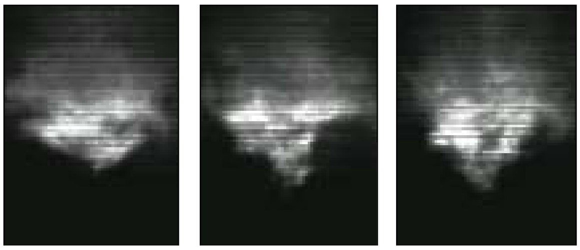

Figure 7 Examples of the instantaneous flame pictures

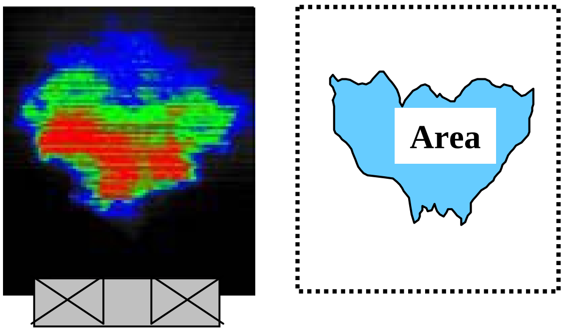

Figure 8 Flame configuration

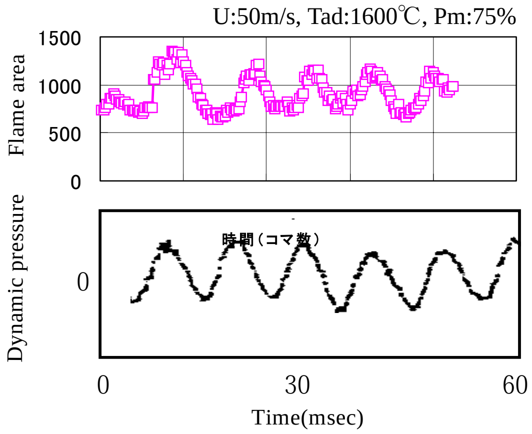

Figure 9 Fluctuations of the flame area and dynamic pressures

From these results, it is found that there are close relations between the flame behaviors and the dynamic pressures. The flame moves with the dynamic pressure periodically, and the amplitude of flame fluctuation is directly proportional to the amplitude of dynamic pressure. Further studies will be performed about this to understand the combustion oscillation.

Comparison of dynamic pressures in both combustion tube and resonator

The resonators were designed so as to coincide the resonance frequencies with 70Hz, 270Hz. The effectiveness of the resonator which can reduce the dynamic pressure in the combustor was already reported in our previous papers (Yamanaka et al. 2000). Figures 10 and 11 show the results. The vertical axis presents the dynamic pressure ratio to the dynamic pressure before applying the resonator. In the case of reducing the acoustic type oscillation, there is an optimum volume of the resonator to minimize the dynamic pressure(point③in Fig 10). On the other hand , in the case of reducing the Helmholtz type oscillation by applying a resonator, it is observed that acoustic type oscillation appears as Helmholtz type oscillation becomes small(Fig.11).

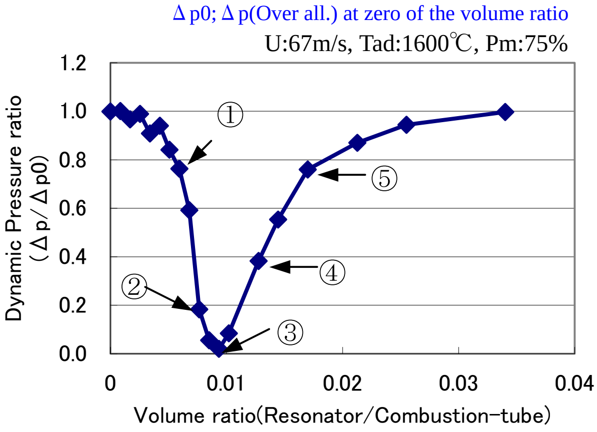

Figure 10 Effect of the resonator on dynamic pressure
(in case of the acoustic type oscillation: 270Hz)

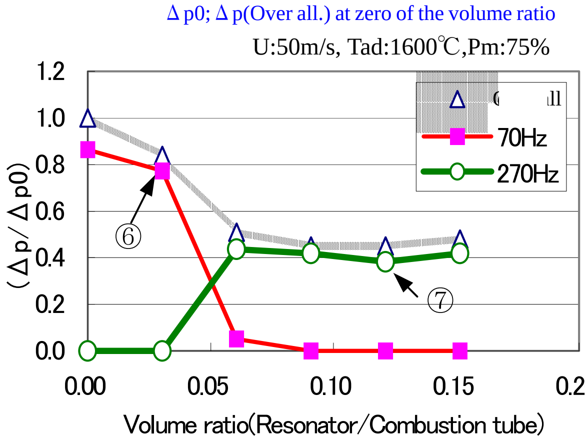

Figure 11 Effect of the resonator on dynamic pressure
(in case of the Helmholtz type oscillation: 70Hz)

The dynamic pressures in both the combustion tube and the resonator were measured to study the performance of the resonator . Figures 12 to 16 show the dynamic pressure signals of 1ch and 14ch at the points of ①,②,③,④,⑤ in Figure10. The 1ch represents the largest dynamic pressure in the combustion tube. The 14ch can represent the dynamic pressure in the resonator whenever the resonator is operated, and the phase differences of dynamic pressures are almost the same at any points in the resonator. Therefore, 1ch and 14ch are selected to evaluate the performance of the resonator. At the point of ①, the dynamic pressure in the resonator is larger than the one in combustion tube. Increasing the volume of resonator(point ②), the dynamic pressure in the combustion tube becomes small. The phase differences of the dynamic pressures in both the combustion tube and the resonator are almost the same(Fig.12 and Fig.13). Increasing the volume of the resonator to the point ③, the dynamic pressure in the combustion tube becomes minimum. In this point, the phase differences of dynamic pressures in both the combustion tube and the resonator is almost reversed(Fig.14). Increasing the volume of resonator further, the dynamic pressures in both the combustion tube and resonator become large, and then the dynamic pressure in combustion tube become larger than the one in resonator(Fig.15 and Fig.16). Although the phase difference of the dynamic pressures both in the combustion tube and in the resonator is reverse in these regions, there is no effect of the resonator to reduce the dynamic pressure in the combustor. It can be considered that the dynamic pressures in resonator are relaxed with the large volume of resonator. Therefore, the dynamic pressure in the resonator becomes smaller than the one in the combustion tube. In this case, there is no effect of the resonator to reduce the dynamic pressure in the combustion tube.

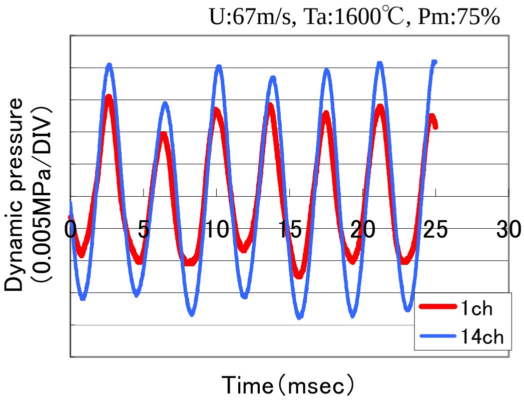

Figure 12 Pressure fluctuations in combustion tube and resonator(at point ①)

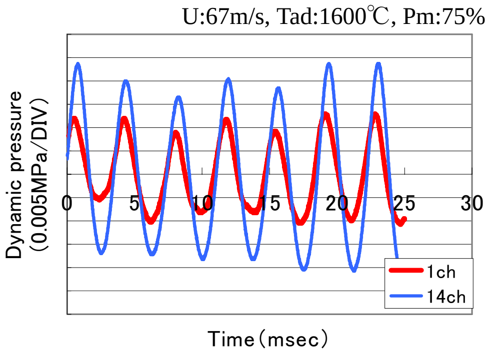

Figure 13 Pressure fluctuations in combustion tube and resonator (at point ②)

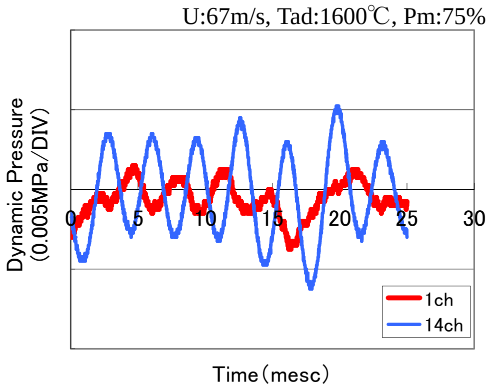

Figure 14 Pressure fluctuations in combustion tube and the resonator(at point ③)

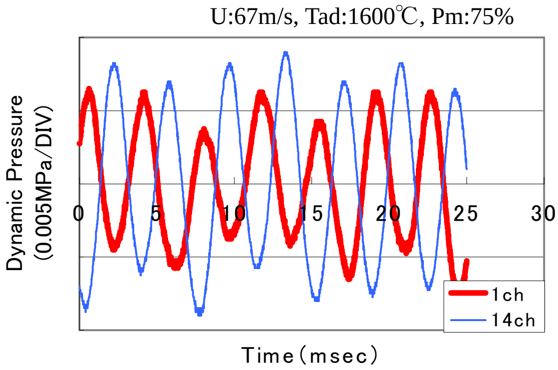

Figure 15 Pressure fluctuations in combustion tube and resonator(at point ④)

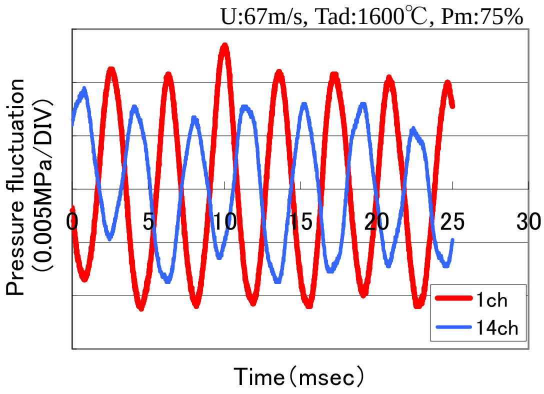

Figure 16 Pressure fluctuations in combustion tube and resonator(at point ⑤)

Figure 17 shows the dynamic pressure at the point of ⑥ in Figure11. Here, Helmholtz type oscillation(70Hz) is dominant. There is almost the same phase difference of the dynamic pressures in both the combustion tube and the resonator. At first, the dynamic pressure in combustion tube is larger than the one in resonator. Increasing the volume of resonator, the dynamic pressures in resonator becomes larger than the one in combustion tube, and then amplitude of the dynamic pressure in combustion tube decreases. Increasing the volume of resonator further, the phase difference of dynamic pressures in both the combustion tube and resonator become reversed, and then the acoustic type oscillation(270Hz) appears as the Helmholtz type oscillation(70Hz) becomes small. The point ⑦ in Figure11 shows the condition around here. Figure 18 shows the dynamic pressure at the point ⑦. At this point, the dynamic pressure in resonator is lower than the one in combustion tube. In this case, the effectiveness of resonator for reducing the oscillation can not be expected.

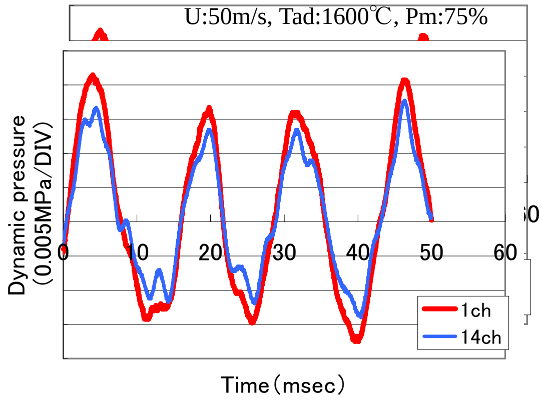

Figure 17 Pressure fluctuation sin combustion and the resonator(at point ⑥)

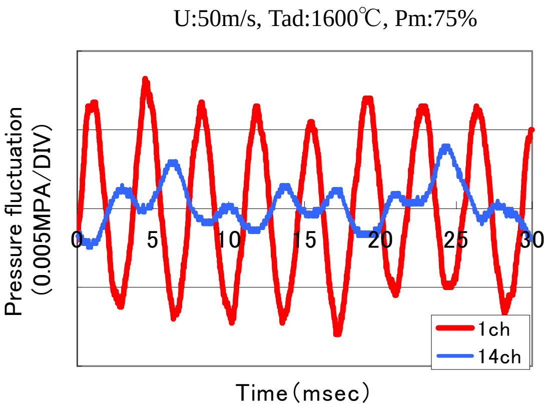

Figure 18 Pressure fluctuations in combustion tube
and the resonator(at point ⑦)

From these results, it is found that the following two conditions are necessary to reduce the dynamic pressures in the combustion tube.

(1)The dynamic pressure in the resonator should be larger than the one in the combustion tube.

(2)The phase difference of dynamic pressures in both the combustion tube and the resonator should be reversed.

Automatic control of the resonator volume to minimize the oscillations

Figure 19 presents the schematic diagram of the control system. There are two resonators which can control the volumes by moving the pistons. The resonator 1 is for the Helmholtz type oscillation, and the resonator 2 is for the acoustic type oscillation. In the case of combustion oscillations for 70Hz and 270Hz, the optimum volume of resonator 1 is about 15 times larger than the resonator 2 according to the equation (1). Where, the cross sectional area of the throat(S) and the throat length (Ls) are constant in the present case. Therefore, the piston of resonator 1 moves faster than the piston of resonator 2. However, there is a time lag to get the effect of the resonator by setting the volume of the resonator. Here, the piston of resonator 1 is controlled so as to move with 5mm/sec and the piston of resonator 2 is controlled so as to move with 1mm/sec. The detail procedures of the controlling system are as follows. The dynamic pressure in combustion tube is measured by the ΔP-probe sensor. A computer analyzed the dominant frequency and the amplitude of dynamic pressure from the signals of ΔP-probe sensor. From these results, the computer makes a judgement regarding which resonator to be controlled, and calculates the position of piston. Then, the signal of the position data is transferred to the motor which moves the piston. This controlling system is operated constantly to minimize the dynamic pressure in the combustion tube.

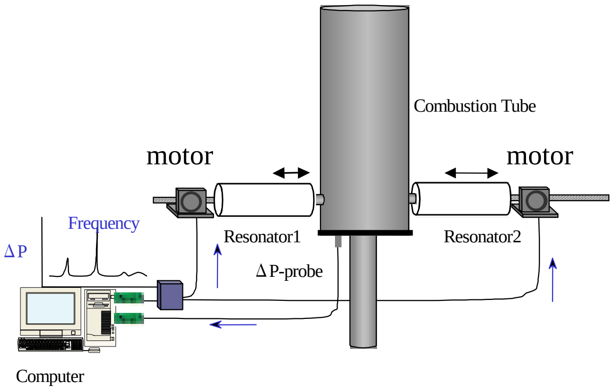

Figure 19 Schematic diagram of the controlling system

Figure 20 presents the result which is derived from the controlling system. Figure 20 shows the dynamic pressures in the combustion tube and the position of the piston. In this Figure, acoustic type oscillation (270Hz) is occurring at first. By applying the controlling system, the amplitude of dynamic pressure shifts to lower levels by controlling the volume of resonator2. In this case, it is not necessary to control the volume of resonator 1.

On the other hand , in the case of reducing the Helmholtz type oscillation by applying a resonator, it is observed that acoustic type oscillation appears as Helmholtz type oscillation becomes small(Fig.11). Therefore, this behavior was checked by increasing the volume of resonator 1 at first without using the controlling system. Figure 21 presents the result. It is found that the acoustic type oscillation(270Hz) appears as Helmholtz type oscillation(70Hz) becomes small. Then, the acoustic type oscillation becomes small by increasing the volume of the resonator 2 as shown in Figure 21. Next, the controlling system was applied in the case of Helmholtz type oscillation(70Hz) occurring. Figure 22 shows the result. By using the controlling system, the dynamic pressures shift to lower levels without appearing the acoustic type oscillation(270Hz) in the process of reducing the Helmholtz type oscillation(70Hz).

Although the controlling system is simple, it is found that the system can achieve large reduction of the oscillation amplitude.

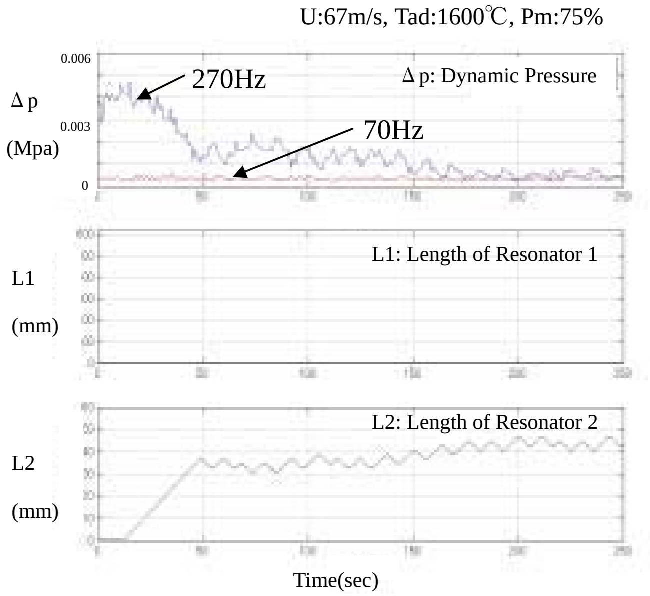

Figure 20 Test result with the controlling system
(In case of applying to acoustic type oscillation)

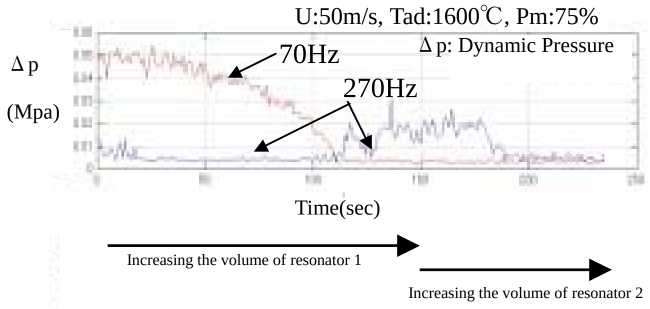

Figure 21 Test result without the controlling system
(In case of applying to Helmholtz type oscillation)

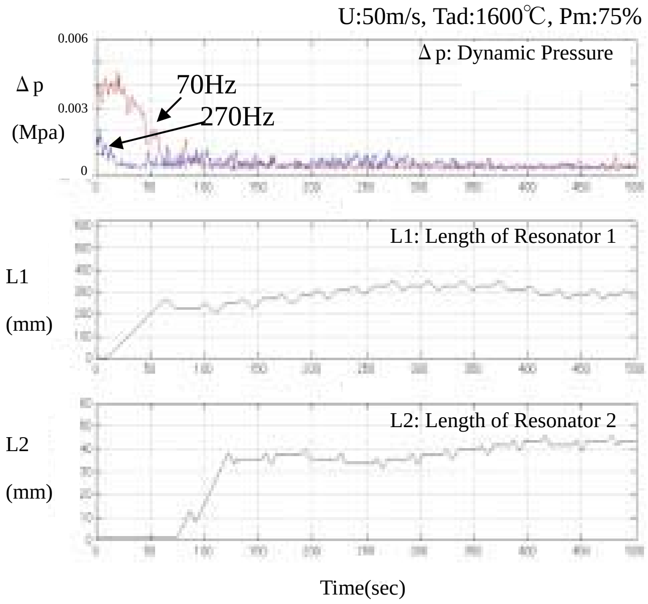

Figure 21 Test results with the controlling system
(In case of applying to Helmholtz type oscillation)

CONCLUSIONS

To study the reduction of combustion oscillation in the gas turbine combustor, combustion tests were performed by utilizing the premixed combustor which incorporated swirl stabilization and a pilot flame similar to gas turbine fuel nozzle under atmospheric pressure. And then, resonators were applied to reduce the combustion oscillations. In this work, the intensities of flame lights and flame pictures were taken by using the photodiode and high speed video camera at first. The data are compared with the dynamic pressures to study the relations between flame behaviors and combustion oscillations. At second, the dynamic pressures in both the combustion tube and the resonator were measured to study the performance of resonator by changing the resonator volume. Finally, the controlling system which automatically controls the resonator volumes was tested to reduce the combustion oscillations. The results are as follows.

There are close relations between the dynamic pressures and the flame behaviors. The flame moves periodically with the dynamic pressure, and the amplitude of the flame fluctuation is proportional to that of the dynamic pressure.

From the dynamic pressures in both combustion tube and resonator, it is found that the dynamic pressure in the combustion tube can be reduced by satisfying the following two conditions.

・The amplitude of dynamic pressure in the resonator should be larger than that of dynamic pressure in the combustion tube.

・The phase difference of dynamic pressures in both the combustion tube and the resonator should be reversed.

The controlling system, which automatically controls the resonator volume to minimize the amplitude of oscillations based on the dynamic pressure signal in the combustion chamber, is applied to the combustor. It is found that the controlling system can achieve large reduction of the oscillation amplitude in the wide range of operating conditions. In the case of the Helmholtz type oscillation, the acoustic oscillation occasionally appears in the process of reducing the Helmholtz type oscillation. In this case, it is possible to minimize the amplitude of dynamic pressure by using another resonator. Therefore, two resonators are applied in the controlling system, and the effectiveness of the controlling system has been successfully demonstrated.

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