산화제 과잉 예연소기 연소특성 연구

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Research on the Characteristics of the Oxygen Rich Combustion Preburner

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ABSTRACT

An oxygen rich preburner was tested and the responses from the pressure sensors were studied with FFT analysis. Since the limited capability of the static sensor, less than 250 Hz frequency domain was investigated and compared to the results of the dynamic sensors. As a result, 60 Hz harmonics were presented dominant in the combustion pressure and oxygen inlet pressure. While similar harmonics were shown with the dynamic sensor, it indicated that harmonics less than 60 Hz were very minor and the high frequency is more important.

초 록

산화제 과잉 예연소기의 연소시험을 통해 예연소기 각 부위에서 압력을 측정하였다. 측정결과는 FFT를 통해 주파수 해석이 이루어 졌으나 정압 센서의 한계로 인하여 250 Hz 이상의 주파수에는 자세한 연구가 이루어지지 못하였다. 정압 데이터 분석결과 30 Hz의 하모닉스가 연소압과 산소입구에서 관측되었다. 따라서 연소압의 변화는 O/F 변화로 인한 것으로 파악된다. 반면에 동압센서 신호를 살펴보면 정압센서에서 확연히 나타났던 주파수보다 훨씬 더 명확한 주파수가 보다 높은 Hz에서 관측되는 것을 알 수 있었다.

Key Words: Preburner(예연소기), Liquid Rocket Engine(액체로켓엔진), LOx(액체산소), Oxygen rich combustuion (산화제 과잉 연소), Lean burn (희박연소)

1. Introduction

A preburner is on of the key components of the staged combustion engines. The development of the oxygen rich preburner is notoriously difficult because of the difficulties dealing hot oxygen gas. In fact, oxygen rich combustion so called lean combustion is getting more and more attention in the field of gas burner and the turbine because of the NOx control[1][2]. However, the rocket engine

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is very different from the burner. The equivalence ratio of the preburner is 0.226 that is much more less, the mass flow rate and swirl number are larger than those of the gas burner.

To study the extreme oxygen rich combustion, hot fire tests were conducted with the preburners. The O/F in the combustion zone is about 15 and increases upto 60 to cool down the exhaust gas. The pressures measured during the test were studied by FFT analysis. As a result, a low frequency harmonics were found dominant with the results from the static pressure sensors. There were many attempts to explain the low frequency harmonics such as vortex break down, precession of the vortex core and so on[3][4]. However as stated earlier this theories can be hardly applied to the rocket engines. The FFT results tells that the frequency might come from the O/F variation. However the dynamic pressure sensor provided more information. One of them is that once considered as a dominant frequency is less important when the frequency domain is expanded into very high frequency range.

2. Structure of the preburner and hot fire test

The preburner tested is a separable type in which the mixing head and the combustion chamber is divided. Thus, there are the two LOx inlets, one for the mixing head and the other for the cooling channel. Since, the mixing head takes all the fuel, only one fuel inlet is necessary. Refer the [3][4] for the detailed description of the preburner.

Many static pressure sensors along with the dynamic sensor and the thermocouples were installed to monitor the tests. Figure 1 shows the locations and the abbreviation of the sensors.

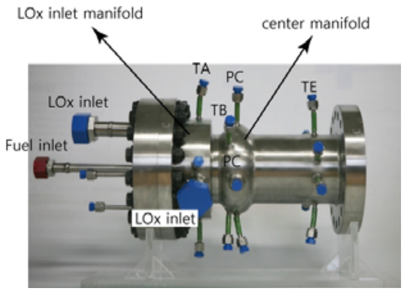

Fig. 1 Sensor Location

In Fig. 1 the capital letters T and P means thermocouple and pressure sensors. The next letter A to E indicate the location. For example, PC means that the pressure sensor installed at the center manifold.

A series of hot fire tests conducted with nominal mass flow rate and reduced combustion pressure. The nominal combustion pressure is 200 bar while the reduced pressure is 80 bar. The low combustion pressure was realized by the large throat size. One of the test condition is shown below.

Table 3 Test conditions

		Aux mode (head/channel)	Main mode
mass flow	LOx [kg/sec]	2.1 / 6.63	3.48 / 10.75
	kerosene [g/sec]	129.67	240.06
Pressure	LOx [MPa]	5.63 / 5.04	9.91 / 8.77
	kerosene [MPa]	6.48	9.68
Time	[sec]	6.6 - 8	10 - 16

Figure 2 is the responses of the static pressure sensors. The data aquisition rate, f_s is 1000 Hz, or time interval, Δt is $\frac{1}{1000}$ sec

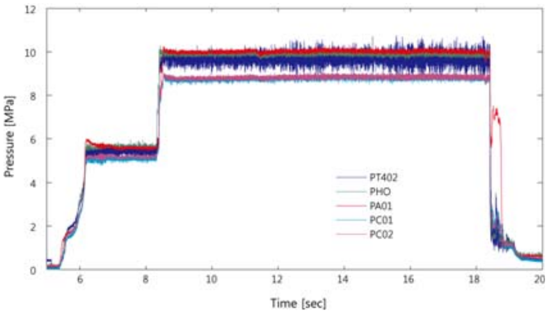

Fig. 2 Pressure of the various locations, PT402: kerosene inlet, PHO: LOx head inlet, PA01, LOx channel inlet manifold and PC01, PC02: LOx pressure in the center manifold.

In Fig. 2, it is shown that the test was performed with two steps. The first low combustion pressure region called auxiliary mode was prepared for smooth pressure development inside the chamber. The second higher pressure zone is called main mode in which nominal mass flow rate was used. A similar experiment was conducted by Haeseler et. al.[7] and their combustion pressure reached to 125 kg/cm^2 with subscale engine.

3. FFT analysis of main combustion zone

FFT analysis was introduced to study the pressure oscillation shown in Fig. 2 in main mode. The number of the total sample, N is 8884 and the sampling frequency, f_s is 1000 Hz. The fundamental frequency, f_o is defined by Eq. 1 and the Nyquist frequency, f_N that is the half of the sampling frequency, are 0.0563 Hz and 500 Hz, respectively.

$$f_o = \frac{f_s}{N} \tag{1}$$

The simple multiplication of the FFT results by their conjugates was used for the magnitude as shown in Eq. 2.

$$\begin{aligned} Y(f) &= FFT\{y(t)\} \\ A_i &= Y(f_i)\,Y(f_i)^* \end{aligned} \tag{2}$$

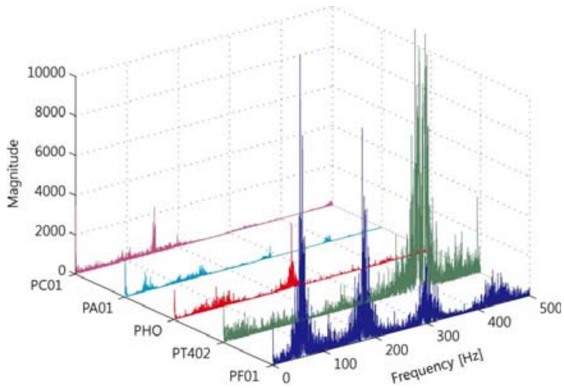

Fig. 3 FFT results of the pressures of the main mode

Figures 3 shows the dominant frequency at the each location of the preburner. It is noticed that the combustion pressure which is PF01 has the harmonic frequencies of 60, 180, 300 and so on. The magnitudes of the frequencies decrease as the frequency increases. The dominant frequencies does not seem to have any special relationship between the locations.

Since, the dominants frequencies of the each locations did not seem closely related, other fluctuation source was needed to be found. The first candidate was the O/F ratio, because small oscillation of the O/F ratio can result considerable change in the combustion pressure [1]. Figure 4 is the O/F FFT plot of O/F ratio and combustion pressure (PF01) variations. It is shown that the dominants frequencies are almost identical.

In Figure 5, the fuel supply shows no

dominant oscillation frequency but the LOx supply has same frequencies as the O/F does. Therefore it can be concluded that the 30 Hz harmonics is originated from the fuel supply line.

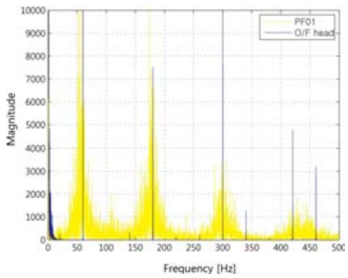

Fig. 4 Frequencies of the combustion pressure (PF01) and O/F ratio change

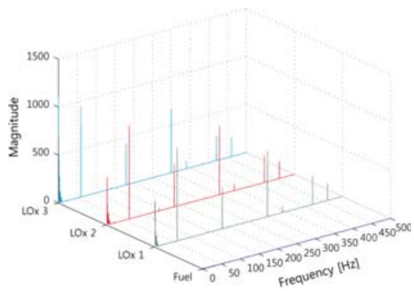

Fig. 5 Volume flow fluctuation frequencies

The sampling rate of the dynamic sensor is far faster than the static pressure sensors. The time resolution, Δt is 3.90625×10^{-5} sec and the sample rate, f_s is 25,600 Hz. The Nyquist frequency, f_N is 128,00 Hz. Figure 6 is the FFT plot of the combustion pressure, DPC. The frequency domain is expanded up to 500 Hz to be compared with the Fig. 3, 4 and 5 even though f_N is 128,00 Hz.

In Fig. 6 the results from the dynamic sensors show a bit different patterns. The dominant harmonics of Fig. 3, 4 and 5 seem to turn out the minor frequencies. It is much clearer if the frequency domain is narrowed.

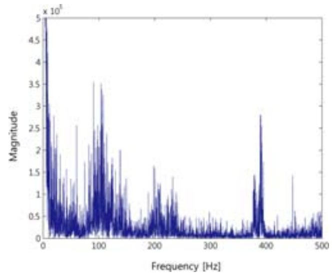

Fig. 6 FFT results of the dynamic sensor of the combustion pressure

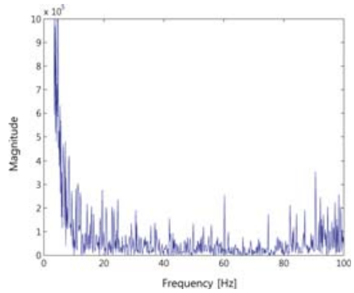

Fig. 7 FFT results with the narrowed frequency domain

Figure 7 still shows the 60 Hz harmonics but compared with Fig. 6 the magnitude is much smaller than the other dominant frequencies. Thus it can be deduced that even though the O/F oscillation affects the combustion pressure, it is not sufficient to make a conclusion with the static pressure results. In addition, the dynamic sensor results show that very the low frequency such as 60 Hz is less important than the higher frequency.

In fact, the around 100 Hz harmonics appeared in almost every tests. Several possible reasons were considered for this 100 Hz harmonics. One is the vortex break down and another is the precession of the vortex core (PVC). However these theories produced much higher frequencies, not even close to the 100 Hz. Only the dynamics analysis with the combustion delay time resulted in reasonably closed result. However, it may requires much more efforts to find out the cause of the harmonics.

4. Conclusion

(1) Hot fire test was presented.
(2) The low frequency harmonics found by the static pressure was due to the O/F oscillation.
(3) Vortex breakdown and PVC were failed to describe the 100 Hz harmonics.
(4) The dynamics analysis with the combustion delay time resulted in reasonably closed result.

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