Determination of Cyclogram for Liquid-Propellant Rocket Engine

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Abstract

A vertical test stand based on launcher propulsion system was constructed and several tests for the determination of cyclogram were carried out. To make an accurate estimation, static and dynamic pressures were measured and analyzed. Especially, static pressure measurements using fast response sensors without extension tubes were used to determine operation sequence more evidently. The standard operation times of final valves were determined in cold flow tests with an engine head, and fire formation time in combustion chamber was checked in an ignition test with an ignitor only. On the basis of these tests, ignition sequence was established and combustion test cyclogram was finally determined. According to combustion test, test results were well matched with the determined cyclogram within 0.05 sec.

Key Word : Cyclogram, Vertical Test Stand, Rocket Engine, Combustion Test

Introduction

Combustion tests of liquid-propellant rocket engines are tests of a large scale which need lots of man power and high cost, so that only limited time of tests can carried out within budget and time. Thus, test engineers are concerned with the insurance of safety so much and they must predict the test situation exactly and prepared properly to perform the tests successfully and safely. In the case of liquid propellant rocket engine tests, an ignition moment is the most important and the most dangerous stage of combustion. Traditionally the decision of manifold filling time, ignition time, and the forth highly depends on engine designers' and test engineers' experience and subjectivity, but nowadays the development of measurement system makes the determination more clear and objective and the reliability of data analysis can be improved.

So far Korea Aerospace Research Institute(KARI) has developed a liquid propellant rocket engine based on national space development project and carried out engine verification tests on a horizontal test stand. Concurrently, propellant feeding system for a launcher also has been developed. After each development program was done, a vertical test stand was constructed and combustion tests were performed to confirm the whole propulsion system for a launcher which has a propellant feeding system and an engine individually developed. Because an engine is installed in vertical position and feeding system components(e.g, valves, tubes, regulators, etc.) are different from a horizontal test stand where engine verification tests are done, the feeding characteristics of propellants to an engine are changed, which alter an ignition process. Thereby several cold flow

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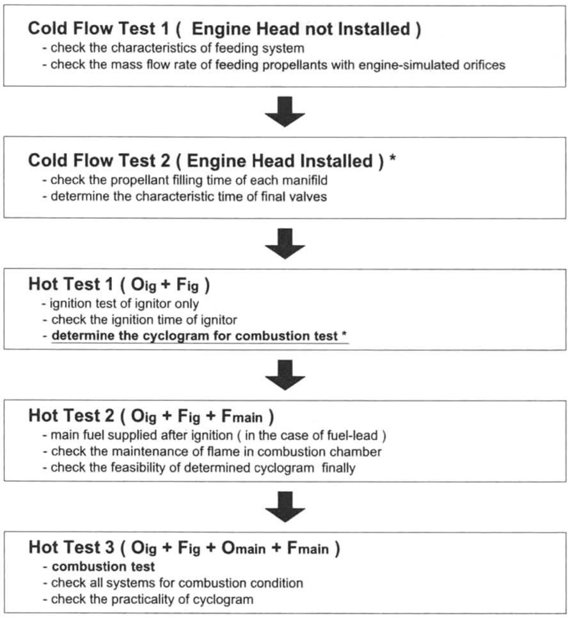


Fig. 1. Test Procedure to Determine Cyclogram

tests have been performed, so that an ignition sequence could be established before combustion tests.

In general, unless an ignition process should be set up and executed as planned, hard start with excessive propellants in combustion chamber, spontaneous instabilities and the like could be happened during combustion tests, therefore not only an engine but also a whole test stand could be severely damaged. And the ignition sequence of combustion test on a vertical test stand with launcher's feeding components is the same as a real launcher, hence the determination of ignition sequence of combustion test on a vertical test stand is of high significance.

For the decision of ignition sequence, several tests were carried out with the procedure shown in Fig. 1. First, during cold flow test, the reliability of feeding system operation and propellant flow rates have been checked using orifices which simulates engine combustion pressure. However, in this test, an accurate characteristic time to fill manifolds of final valves could not be found out because engine manifold shape and volume were not simulated exactly. Therefore, another cold flow test with an engine head installed was required to set up the standard operation time of final valves to fill each manifold.

After these cold flow tests, fire formation time from ignition command was checked by an ignition test using an ignitor only. With the results of cold flow test and ignition test with an engine head installed(second and third step of Fig. 1), the ignition sequence of propulsion system can be finally determined. During engine verification tests carried out on a horizontal test stand, fuel-lead ignition was selected for combustion. So that hot test No. 2 (shown in Fig. 1) was carried out to confirm the fire maintained by an ignitor after main fuel supplies except for main oxidizer supply to an engine. Then, a combustion test of the whole propellant feedings at on-design condition was finally put into operation.

In this paper, the determination of standard operation time of final valves throughout cold flow tests with an engine head, a cyclogram and the results of a combustion test on a vertical test stand are introduced.

Determination of Cyclogram

Cold Flow Test for Ignition Sequence

A horizontal test stand is the facility to characterize a rocket engine during steady operation and has all kinds of measurement systems. Therefore, to decide an ignition sequence in this system, several tests with very similar procedure shown in Fig. 1 have been also carried out, and then an ignition sequence has been determined with overall analysis on acquired data of static pressures, dynamic pressures, flow rates, thrust, an so forth.

However, on a vertical test stand, limited numbers of static, dynamic pressure sensors and vibration sensors were mounted and propellant volume flow meters were removed after engine installation because all measuring equipments were installed on the basis of a real launcher system. Thereby the determination of an ignition sequence and the characteristics of an engine had to be decided by these limited numbers of acquired data.

To acquire data, XT-190 series static pressure sensors were used for engine manifolds and XTE-375 series for combustion chamber, which are produced by Kulite Semiconductor Products, Inc., and 102A series, made by PCB Piezotronics, Inc., were used to measure pressure pulsations. Generally, if the size of sensor is large and weight is relatively heavy, it is almost impossible to mount a sensor on an engine directly because connection part can be easily broken by mechanical vibration of combustion, hence most of static transducers need extension tubes from a measuring part to a sensor. But XT-190 series, which weighs only 4 g, can be installed on manifolds directly to an engine without extension tube. Static pressure sensors for a combustion chamber have extension tubes of 40 cm in length to protect from the high temperature of combustion gas. Basically dynamic pressure sensors are not mounted for a launcher, but are mounted additionally for a stability-rating. The installation locations of sensors are shown in Fig. 2.

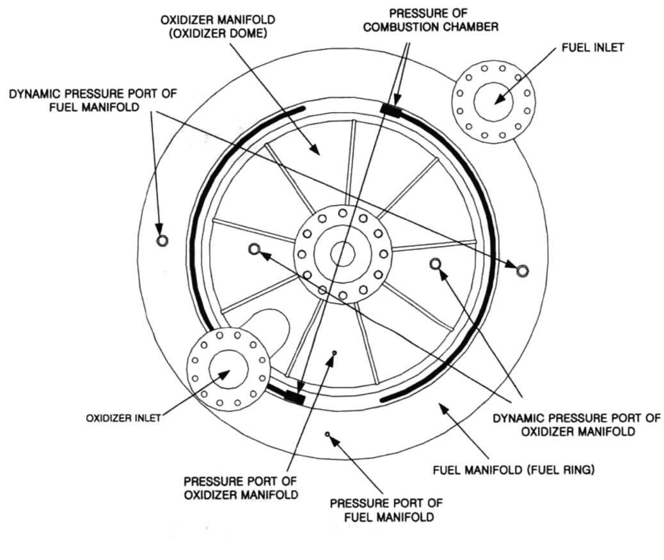
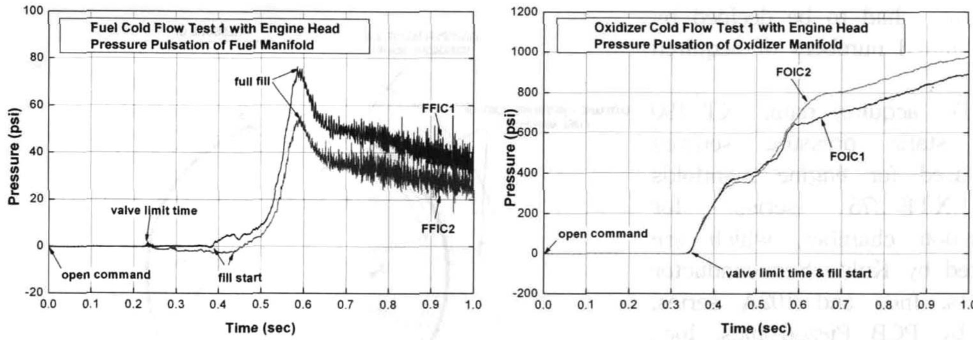


Fig. 2. Schematic of Position of Sensors

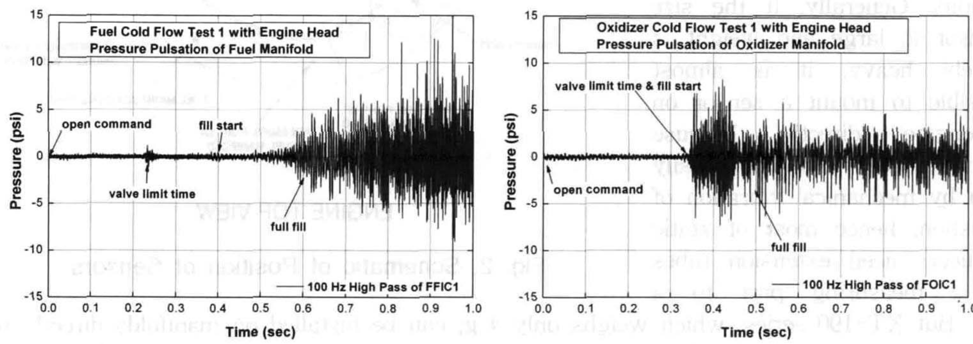
Typical measurement method of measuring static pressures is using extension tube which has the characteristics of time delay in acquired data in spite of using fast response sensors. But, by the reason of fast response and no extension tubes, static pressure transducers used for this propulsion system can display the pressure behavior at almost same time(less than 0.05 sec.), compared with dynamic pressure sensors. Therefore, static pressure signals of the present system may be considered as very important parameters, which show manifold pressure behavior almost on time.

Several cold flow tests with an engine head (cold flow test 2 in Fig. 1) have been carried out and the results of these tests are shown in Fig. 3. Test time zero on X axis means opening command time in Fig. 3. Fig. 3(a) shows two dynamic pressures of each manifold in the first test. Fig. 3(b) shows one of 100 Hz high pass signals of dynamic pressures in Fig. 3(a) and Fig. 3(c) illustrates static pressure signals of two different tests. To begin with a fuel manifold, it is found that static and dynamic pressure signals(Fig. 3(a) and (c)) rise at about 0.4 sec., test time, overshoot, at about 0.6 sec., and become stable. In 100 Hz high pass signals (Fig. 3(b)) pressure pulsation has also been built up at about 0.6 sec. either. In an oxidizer manifold, static and dynamic pressures rise at about 0.35 sec. test time, and become stable at about 0.5 sec. Oxidizer manifold static pressure signals show much higher levels than fuel manifold because oxidizer flow in injector orifices is not purely liquid, but two-phase flow with vaporized gas due to atmospheric back pressure.

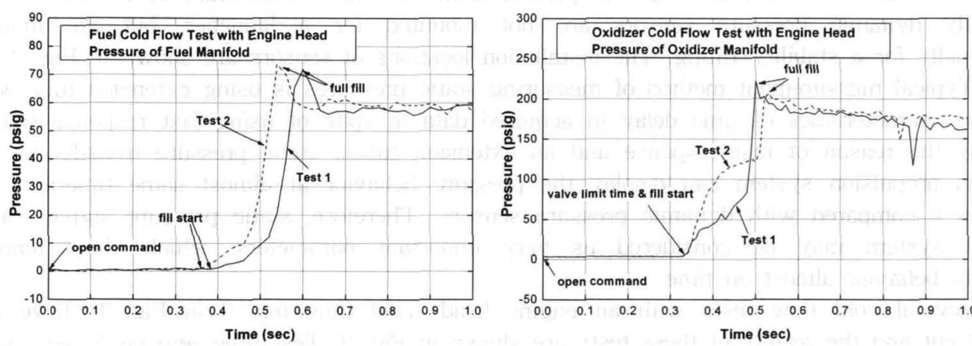
Final valves are mechanical components, so that valve acting time shows slightly different on daily operation. Accordingly, the time analysis of test results was done by unit of 0.05 sec. and then final valve operation standard times can be settled, shown in table. 1. To prevent of main propellant feeding in the reversal order, relatively later time of fuel valve and earlier time of oxidizer valve were selected for standard operation times.



(a) Dynamic Pressure of Fuel & Oxidizer Manifold



(b) Dynamic Pressure of Fuel & Oxidizer Manifold after 100 Hz High Pass



(c) Static Pressure of Fuel & Oxidizer Manifold

Fig. 3. Cold Flow Test with Engine Head for the Determination of Cyclogram

Table 1. Determined Standard Operation Times of Final Valves Based on the Cold Flow Test with an Engine Head

	Open Command	Valve Open	Propellant Injection Begin	Manifold Full Fill
Fuel Final Valve	0 sec.	0.2 sec.	0.4 sec.	**0.6 sec.**
Oxidizer Final Valve	0 sec.	0.3 sec.	0.35 sec.	**0.5 sec.**

To confirm the reliability of the above test results, manifold filling time is estimated by simple calculation. During cold flow test without an engine head, system maximum volume flow rates were found out without orifices simulated combustion chamber pressure, which were 22 liter/sec. for fuel side and 55 liter/sec. for oxidizer side. Then, manifold volumes were divided by maximum volume flow rates, valve acting times were added to those, the whole manifold filling times can be estimated as shown in table. 2. These results agrees with the determined standard operation times of final valves based on the cold flow tests with an engine head(table 1.) within 0.05 sec.

Table 2. Estimation of Manifold Filling Time Based on Simple Calculation

	Maximum Volume Flow Rate of Test Stand [liter / sec.] (a)	Manifold Volume [liter] (b)	Filling Time [sec.] (c)=(b)/(a)	Valve Time from Command to Valve Limit Signal [sec.] (d)	Estimated Whole Filling Time from Command to Full Fill [sec.] (c)+(d)
Fuel	about 22	about 9.5	about 0.43	about 0.22	**about 0.65**
Oxidizer	about 50	about 6	about 0.12	about 0.35	**about 0.47**

Determination of Cyclogram

After final valve standard operation times were set by the cold flow tests with an engine head (cold flow test no. 2 in Fig. 1), fire build-up time is measured by an ignition test with an ignitor only(hot test no. 1 in Fig. 1) with RTD type temperature sensor installed at the exit of diverging section of combustion chamber, and it is found out that the fire was formed within 0.2 sec. after ignition command.

To determine a cyclogram, the principles as follows are applied for safe ignition.

- **The time of fuel final valve opening command must be engaged after fire formed in combustion chamber by ignitor**; if propellants enter a combustion chamber before the existence of heat resource generated by an ignitor, it may be possible of hard start caused by excessive propellant existence in combustion chamber, which may damage both engine and test facility severely. To secure an engine and facility from the above mentioned situation, fuel final valve opening command should be engaged after 0.2 sec., test time, which is fire formation time in combustion chamber by an ignitor. As a result of fuel final valve's 0.2 sec. command application, actual fuel injection start timis 0.6 sec. in test time.
- **Oxidizer injection start time is set on fuel manifold full fill time**; even though an ignition sequence for the present engine is fuel-lead, it is recommended that time difference must be as short as possible. Therefore an oxidizer injector start time is set on fuel manifold full filling time, which is pressure-overshoot point in fuel manifold.

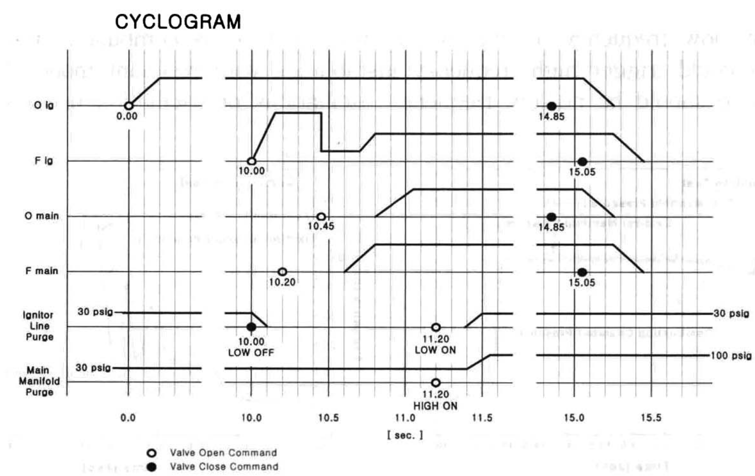


Fig. 4. Cyclogram Determined by Engine Installed Cold Flow Test

On the basis of the above test results and principles, a cyclogram for combustion test is determined as illustrated in Fig. 4. In this Figure, the pressure rising time of oxidizer is 0.25 sec. instead of 0.15 sec. (in table 1), because combustion formation time must be taken into consideration.

Before a combustion test with the whole propellant feeding, a hot test with an ignitor and main fuel except oxidizer feeding has been carried out (hot test no. 2 in Fig. 1). When fuel injection starts to an engine, it is possible that heat resource could be extinguished. Furthermore, if oxidizer injection starts with local heat resource, which is not completely extinguished, combustion can be resumed but build-up process can be much slower. In this case, propellants can enter to combustion chamber without complete burning due to insufficient heat resource and can be re-ignited by local heat existence. It means that hard start can be happened owing to excessive propellant in combustion chamber. Because of the above reasons, the existence of fire in combustion chamber after main fuel feeding has to be checked to secure safety before the whole propellant feeding combustion test. During this test, the performance characteristics of components except oxidizer final valve can be checked once more, and the reliability of cyclogram is finally confirmed.

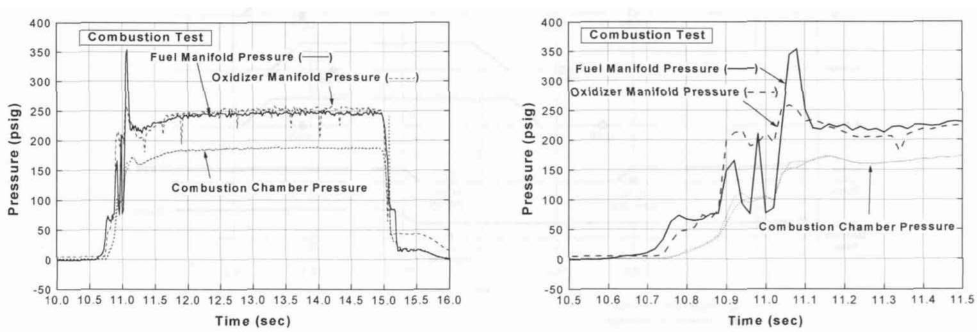
Combustion Test

After all cold flow tests introduced in the above, a combustion test with the whole propellant feeding has been performed. A combustion test was carried out based on the determined cyclogram of Fig. 4, and the results of this test are shown in Fig. 5.

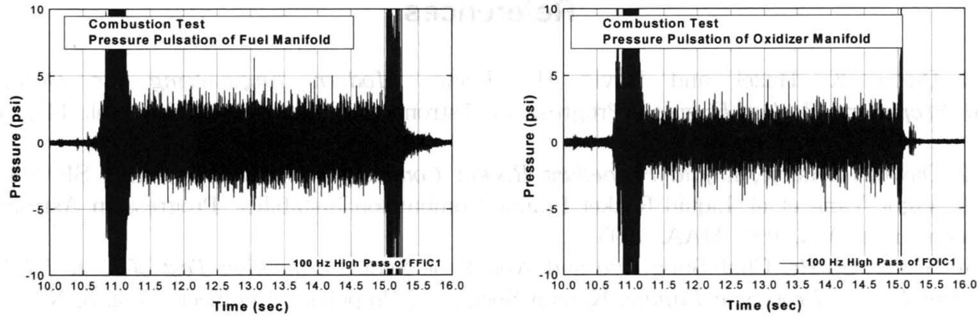
In Fig. 5(a), actual propellant injection times of a combustion test are well agreed with destination times of the previously determined cyclogram within 0.05 sec.

The results of dynamic pressure pulsations of manifolds after 100 Hz high pass filtering are shown in Fig. 5(b). To rate the stability of combustion, it is the best way to measure combustion chamber dynamic pressure, but in this test stand for a launcher system, chamber pressure pulsations are not measured directly due to the characteristics of test facility. Nevertheless, the dynamic pulsations of propellant manifolds can reflect the condition of combustion chamber almost directly with both pulsated time and amplitude. Thus, from the obtained results, it can be said that the present combustion test is very stable because the pressure pulsations of manifolds are less than 3~4 psi without specific frequency.

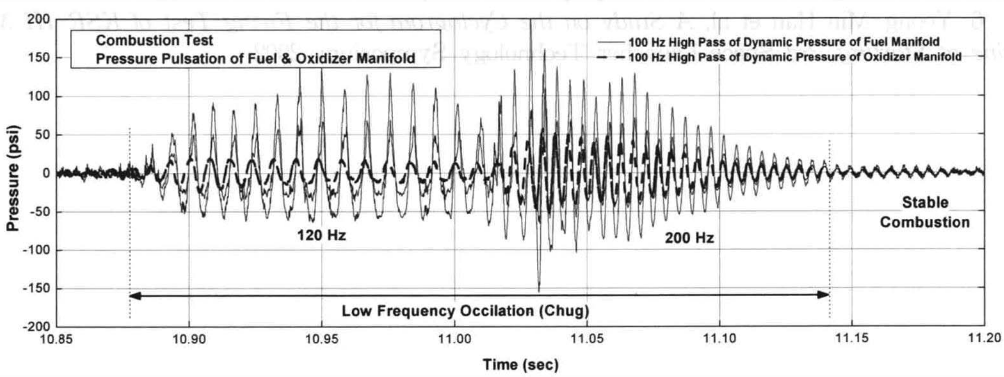
The manifold pressure pulsations during ignition transient period are shown in Fig. 5(c). 120 Hz, and then 200 Hz pulsations have been appeared for about 0.25 sec. after ignition and faded out immediately while chamber pressure reached at steady state condition. Low frequency oscillations , called chug, putt-putt, groaning, etc., was appeared, which were caused by or affected to feeding system. Generally, low frequency oscillations are not specified as combustion instabilities itself, but sometimes it could trigger high frequency instabilities with resonant mode. Therefore, it is desirable that there should be no low frequency oscillations or oscillation periods should be as short as possible.



(a) Static Pressure of Manifolds & Combustion Chamber



(b) Dynamic Pressure of Fuel & Oxidizer Manifold



(c) Dynamic Pressure of Fuel & Oxidizer Manifold during Combustion Starting Transient Period

Fig. 5. Combustion Test Results Based on the Determined Cyclogram

Combustion pressure has been reached rapidly at steady state level. Pressure build-up has started at about 10.75 sec. (in Fig. 5(a)) and combustion has become stable at about 11.15 sec. (in Fig. 5(c)), thus it can be said that engine combustion pressure is build up within about 0.4 sec. in this propulsion system.

Conclusions

In a rocket engine operation, the accurate determination of ignition sequence is very important not only to achieve the stable combustion, but also to secure safety. Although the limited numbers and kinds of measurement systems are applied to combustion tests on a vertical test stand similar to a real launcher system, a successful ignition is achieved by precise measurement and detailed analysis. Particularly, fast response static and dynamic pressure measurement systems are very important and useful equipments for both the accurate determination of ignition sequence and stability rating of combustion.

Compared with the results of combustion test, it is shown that the determined cyclogram is accorded with the actual combustion procedure within 0.05 sec. Consequently, this method of the determination of cyclogram, especially ignition sequence, is to be a proper approach and can be a useful reference for other liquid propellant rocket engine combustion test.

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