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Low frequency instability in laboratory-scale hybrid rocket motors

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ABSTRACT

Hybrid rocket combustion frequently displays a sudden amplification of combustion pressures leading into low frequency instability (LFI) with peak frequency of 10–20 Hz. A series of experimental tests was designed to examine the triggering mechanism of LFI, which occurred at a certain combustion condition. To this end, a couple of parameters was selected and the sensitivity of each parameter to instability was evaluated including volume ratios between main and post chambers, oxidizer mass flow rates, and solid fuel types. The results showed that the initiation of LFI was related to the flow modifications caused by vortex shedding and volume ratios between main and post chambers. Once LFI was initiated at a certain chamber configuration, the variation of oxidizer mass flow rates and the use of different solid fuel did not alter the triggering mechanism of LFI. Additional attention was focused to understand the critical role of vortex shedding on the initiation of LFI in the post chamber. The results confirmed that pressure oscillations by the thermal lag of solid fuel could be suddenly amplified, which leads to LFI in the case of resonating with unknown sources of pressure oscillations associated with vortex shedding in the post chamber. However, the details of triggering mechanism and the coupling of vortex shedding with additional pressure perturbations still remain unresolved.

1. Introduction

Combustion in hybrid rocket motors is a relatively complex procedure to understand because of complicated coupling with fuel regressions, convective heat transfer, and diffusional flame in the turbulent boundary layer of chemically reacting flow. Combustion in hybrid rocket motors displays usually stable characteristics compared to other conventional chemical rockets such as solid and liquid rockets. Nonetheless, typical oscillations with a peak frequency much lower than acoustic modes were frequently found. Even though the causes of the instability are not clearly understood yet, it is suspected that a coupling of various types of pressure oscillation from different sources is the primary cause of low frequency instability (LFI).

A summary of physical explanation of LFI mechanism in hybrid rocket motors was addressed in Ref. [4]. This includes the response of low impedance oxidizer feeding system, combustion response to externally imposed pressure oscillations, periodic accumulation and break-off of melted layers from the fuel surface, and the time lag of vaporization and the combustion of liquid droplets. Each mechanism seemed to be responsible for generating a typical frequency range of oscillation based on the characteristics of primary responses. For example, low frequency oscillations (≤ 100 Hz) are the results of coupling of oxidizer feeding system with pressure oscillations due to time lag responses of solid fuel. However, the unbounded high frequency pressure oscillations (>1000 Hz) usually observed in solid and liquid propulsion systems were seldom found in hybrid rocket combustion. Instead, low frequency oscillations less than 50 Hz were dominantly observed.

Many studies have been investigated on the initiation mechanisms of LFI. Jenkins et al. [4] studied low frequency oscillations with a peak frequency of about 10 Hz using 1-D theoretical model. In particular, they investigated a filling time of oxidizer flux in the motor as the primary causes of low frequency oscillations by using a modified characteristic length (L^*). Lee [7] theoretically suggested that a transient behavior of thermal response of the solid fuel to quasi-steady heat input from the gas phase could be the initiation mechanism of low frequency oscillations. This is generally known as thermal lag oscillations, mainly observed in solid rocket motors due to the different thermal response of gas and solid phases to heat transfer from gas phase.

Karabeyoglu et al. [5] revealed that LFI was the result of complicated coupling of thermal lag of solid fuel with the boundary layer adjustment to external perturbations in hybrid rocket combustion. They proposed a linearized theory based on the mathematical perturbation method in order to predict the initiation of low frequency pressure oscillations. The results showed a good

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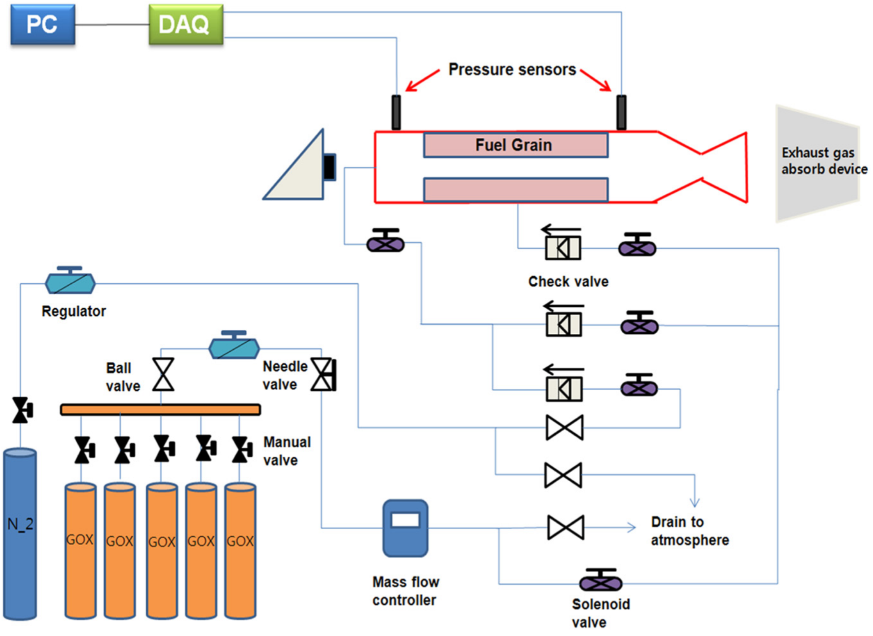

Fig. 1. Schematic of experimental set-up.

agreement with experimental data of pressure oscillations with a peak frequency up to 50 Hz.

Boardman et al. [1] observed sudden amplification of pressure oscillations during combustion processes. FFT analysis confirmed that the instability frequency lies in the range of less than 500 Hz. A peak frequency less than 50 Hz was dominantly identified in the spectral data. But, their study did not address the causes of combustion instability of low frequency. Korting et al. [6] also found that pressure oscillations were suddenly amplified during the combustion. Though the results did not include the spectral analysis of pressure oscillations, they suspected that the sudden increase in the regression rate was directly associated with the abrupt amplification of low frequency pressure oscillations.

Carmicino [2] performed a series of combustion tests with various injector configurations. The test results with radial type injectors showed combustion instability with a peak frequency of 10–30 Hz. They suspected the resonance of pressure perturbations due to unsteady heat releases in the post chamber and acoustic excitations of the main combustor as a triggering mechanism of combustion instability. They claimed that unsteady heat release was possibly related with periodic formation of large-scale vortex shedding into the post chamber producing additional pressure perturbations. However, their study did not account for the effect of flow modifications in the different chamber configurations such as chamber volume ratio, post chamber length, fuel port diameter, etc.

Meanwhile, Greiner and Frederick [3] conducted combustion tests to examine the effect of post chamber volume on the occurrence of instability in hybrid rocket combustion. They found that a sudden amplification of pressure oscillations occurred only at a certain value of volume ratio of main and post chambers. Unfortunately, no further reports were published addressing the correlation between the triggering mechanism of LFI and volume ratio.

Even though previous studies suggested the geometric chamber configuration can be a controlling parameter in determining the appearance of LFI, there are no comprehensive studies to bridge the gap between experimental observations and physical understandings on the triggering mechanisms of LFI. In this study, a series of experimental tests was designed to investigate the triggering mechanism of LFI, which was suddenly amplified at a certain condition during the combustion. To this end, a couple of controlling parameters was selected and the sensitivity of each parameter to instability was evaluated, including volume ratios of main and post chambers, oxidizer mass flow rates, and solid fuel types. Also this study was focused on the modification in flow dynamic behaviors over the backward facing step in the post chamber by locating diaphragms at the rear end of fuel. In addition, the effect of time variation of fuel diameters on the initiation of instability was investigated.

2. Design of combustion tests

Fig. 1 shows the schematics of the experimental-setup. A series of hybrid rocket combustion tests was conducted with a laboratory-scale motor of GOx and PMMA combinations as an oxidizer and solid fuel, respectively. An axial type injector was used in all tests. Solenoid and check valves were used to control oxidizer feeding. The maximum capacity of mass flow controller was up to 40 g/s in the tests. Nitrogen gas was used to purge after the combustion by the PLC (Programmable Logic Controller) control. Piezo-type sensors were installed to measure the combustion pressure. DAQ board and Labview program were also implemented for data acquisition process. Dimensions of the baseline fuel have 50 mm and 20 mm of outer and inner diameters, respectively. In the baseline configuration, the chamber length of main, pre and post chambers were fixed as 200 mm, 45 mm and 75 mm, respectively. A water-cooled nozzle was used, in which a throat diameter and nozzle length were 6.5 mm and 40 mm, respectively.

Table 1 reports a summary of results of all test cases. A baseline test was made as a reference case, in which combustion pressure showed stable behavior and no distinctive LFI was found. Each test case has different configurations of main and post chamber length, whereas pre chamber length was kept unchanged. Here VR is the volume ratio between main and post chambers. The mass flow controller was used to control oxidizer mass flow from 10 g/s to 25 g/s for providing various O/F conditions. The average O/F ratio was calculated by dividing total oxidizer mass by regressed fuel mass during the test ($O/F = \int \dot{m}_{ox} dt / \Delta m_f$).

Tests 1 and 2 were designed to investigate the effect of post chamber length on the initiation of LFI. Test 3 was the case where the main chamber length increased as twice as that of baseline.