Pulsed DB/AB T-Burner Test for Measurement of Combustion Response Function of Solid Propellants

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Abstract

T-burner tests of an Al/HTPB propellant in conjunction with a Pulsed DB/AB Method were conducted to find an acoustic amplification factor. Aluminum-free and aluminum-heavy propellants were examined. Instant surface ignition was successfully made by the use of a supplementary propellant of fractionally higher reaction rate. With the presence of higher aluminum concentration in the propellants, the pressure perturbations were promptly damped down and the pressure fluctuations were no longer dispersive. Addition of aluminum particles into the propellant was advantageous for stabilizing pressure-coupled unstable waves.

Introduction

A large thermal energy by the propellant combustion is released in a solid rocket motor and some of this energy converts to the acoustics energy on account of an acoustics characteristic of the system. The converted energy gives rise to a pressure fluctuation in the T-Burner and the perturbed pressure induces the combustion instability. This pressure fluctuation is classified into bulk mode, transverse mode, axial or longitudinal mode according to the motion of the combustion gas. In this paper we describe an experimental study of the combustion instability in the solid rocket motor. The individual mechanism of phenomenon to be related with the combustion instability as chemical reaction mechanism, heat release structure, combustion mechanism, and acoustic behavior was examined much but relatively, the effects by an interaction of each mechanism were less investigated. Because the characteristic time is largely different from characteristic length for the respective phenomenon in combustion and their differences come to make the complicated acoustic mechanism. Especially it is not easy to express mathematically for the pressure fluctuation of solid rocket motor, consequently in order that the accuracy or the effectiveness of theoretical study increase, currently the experimental approach is a method only instead of theoretical approach. The sensitivity of propellant combustion is connected with acoustic characteristic related to the pressure fluctuation and aerodynamic characteristic in the combustion chamber. The velocity fluctuation usually accompanies the effect by the pressure fluctuation. Since test equipment can't perfectly reproduce internal flow pattern of actual motor, to measure the combustion response for velocity fluctuation with the internal aerodynamics is difficult considerably. However the combustion response for the pressure fluctuation is able to measure easily. Thus a focus of this study fixes for the pressure-coupled combustion instability.

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T-Burner configuration and method

Pulsed DB/AB Method

The various experimental methods were developed for the pressure-coupled combustion instability analysis of the solid rocket motor.[1-3] Generally, the T-Burner which is economic and less restrictive method is used widely. The T-Burner fall into four types : the Standard Method, the Pulsed During Burning/After Burning(DB/AB) Method, the Variable Area T-burner(VATB) Method and the Pulsed VATB Method.[4-5] Standard Method is the method for solid propellant without particulate attenuation material and is simple method which don't need additional equipment because the pressure fluctuation which is able to measure combustion response function, grow up or attenuate naturally. In the case of solid propellant with particulate attenuation material, the pressure fluctuation which is formed spontaneously would be suppressed by the effect of that material and thus an artificial disturbance need for acoustic analysis using the T-Burner. From this, the one of the two methods which is developed is the Pulsed DB/AB Method. It can measure the damping effect of acoustic wave in compliance with the pressure fluctuation. In another one, the VATB Method, propellant samples are used having sufficiently large burn area to provide the spontaneous pressure oscillations in the T-Burner.[6-7] Thus, cylindrical or cup-shaped propellant samples are normally required for the VATB Method when aluminized propellants are tested.[8] The VATB Method is able to measure the damping effect for the pressure and velocity fluctuation. The Pulsed VATB Method is the method where the Pulsed DB/AB Method and VATB Method is combined.[1)]

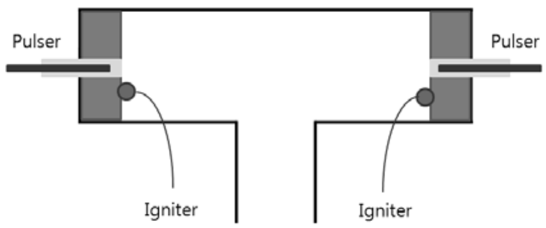


Fig. 1 The Pulsed DB/AB Method

It is known well that the Pulsed DB/AB Method provides more convenient for the interpretation and thus in this study the Pulsed DB/AB Method is used.[8)] The two solid propellant samples are located on both end sides inside the T-Burner. It is shown in Fig. 1 and two pulsers are installed. The pulser used in the Pulsed DB/AB Method introduces the pressure disturbance that is utilized to measure the acoustic energy losses in the T-Burner. For the T-Burner, most tests have been done with the $BKNO_3$ pulser. It is reproducible, and creates sufficient strength to allow the acceptable pressure amplitudes. Respectively, the DB (During Burning) pulser operates in propellant combustion and when propellant combustion completes the AB (After Burning) pulser operates soon as Fig. 2 and they create the artificial pressure fluctuation.

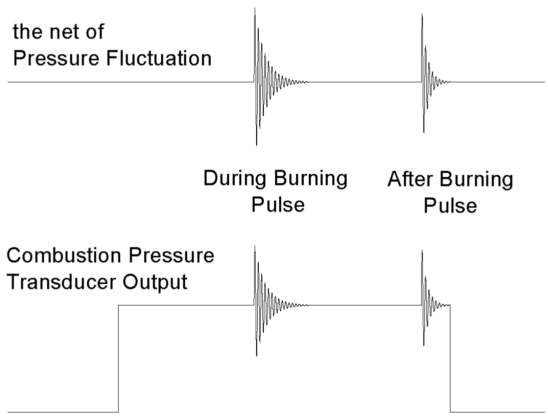


Fig. 2 The During Burning/After Burning (DB/AB) pulse on the combustion pressure

While acoustic fluctuation which is made by DB pulser is amplified by heat release by combustion and is attenuated by the inherent damping structure of system at the same time. Finally acoustic fluctuation by DB pulse is attenuated exponentially because there is no supporting structure of DB pulse. And since combustion complete at the timing of AB pulser operation and heat energy provide no more into acoustic structure of the T-Burner, AB pulse also has no longer amplification structure with the same thermodynamic conditions. Finally acoustic fluctuation by AB pulse is attenuated exponentially. In the acoustic structure of the T-Burner, That is, the amplification effect by heat release by combustion and the attenuation effect by system itself exist at the same time in the period of DB pulse operation and after combustion, in the period of AB pulse operation, the inherent attenuation effect by the T-Burner system exist only. Thus after getting the attenuation coefficient of two pulses by curve fitting, the net effect of combustion is able to be checked by comparison with two attenuation coefficients. The difference between two coefficients means the net effect of combustion as Eq. 1.

$$\left[\alpha_{comb} + \alpha_{sys}\right]_{DB} - \left[\alpha_{sys}\right]_{AB} = \alpha_{comb} \qquad (1)$$

For internal combustion acoustic fields of the T-Burner, the artificial acoustic fluctuation which is formulated with Eq. 2 is assumed as linear. In Eq. 2, p', p_o, α, t, ω are the pressure fluctuation, a mean pressure, the amplification coefficient, time, and the angular frequency, respectively.

$$\frac{p'}{p_o} \approx e^{\alpha t}\cos(\omega t) \qquad (2)$$

T-Burner configuration

The basic hardware for the Pulsed DB/AB method is essentially the same as that described in the T-Burner manual for un-aluminized propellant.[9)] The T-Burner system is organized with main body of alphabet T-shaped, control box, postprocessor for experiment data and power supply for ignition of propellant and operation of pulser. It is shown in Fig. 3.

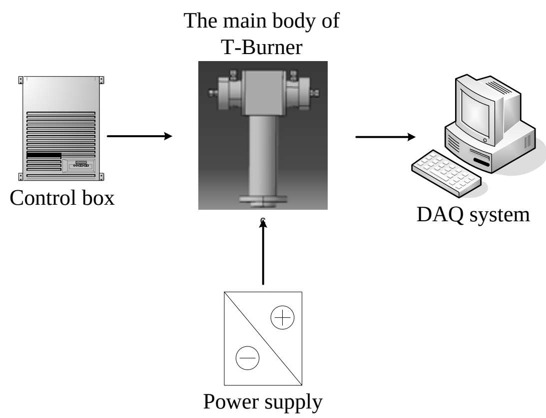


Fig. 3 The System of T-Burner

Considered that the burning time of propellant sample is about 0.7 s, the operating timing of pulser has to be controlled as the level of 1/10 s. This study used the mechanical relay where the control is possible as the level of 1/100 s. PCI-6024E board and LabVIEW 7.0 for data acquisition are used. And the main body design of the T-Burner is based on ref. 6, 10. The schematic of the T-Burner system is shown in Fig. 4.[8, 10)] In order to reproduce a high pressure environment in combustion, the five high pressurized nitrogen gas cylinders which charge with 1500 psi are connected in parallel. The surge tank was used for suppression of the rapid pressure increasing or decreasing and a heat exchanger is used for reduction of thermal load of exhaust gas.

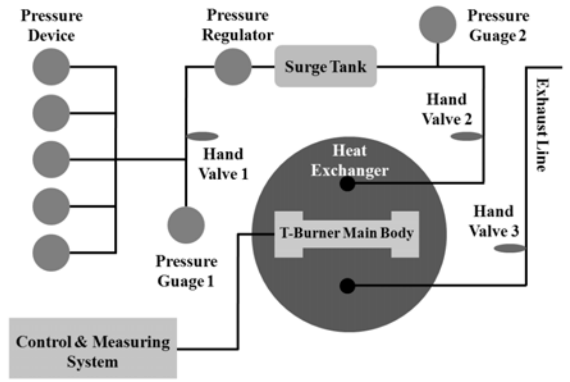
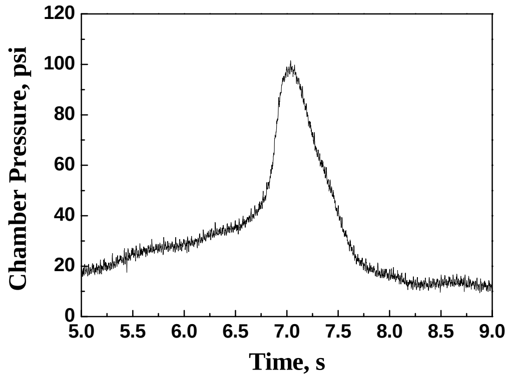


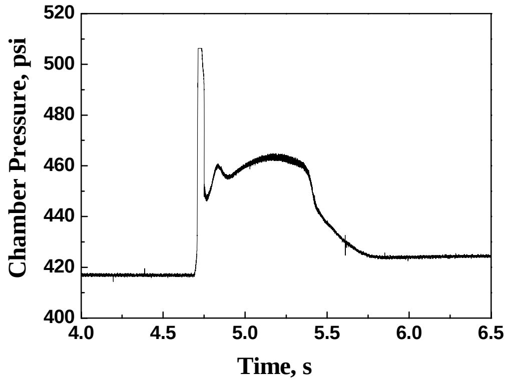
Fig. 4 A schematic of T-Burner

Ignition Supplementary Disk

Since the combustion instability analysis using the T-Burner is based on 1D, the form of the inside of the T-Burner has tube form with the circular section. Thus in order to satisfy 1D, the solid propellant sample which is located at both end side of tube has to burn without changing of burning area. The ignition has to conduct simultaneously on the whole surface to achieve as the aforementioned point of view. In this study, the propellant supplementary disk including combustion catalyst is used as shape of slice which is attached on the surface of propellant. The propellant supplementary disk has the rate of combustion with 4~5 times where it is quicker than the general propellant'. After the igniter is operated, the flame of the propellant supplementary disk fast propagated on the whole surface due to fast burning speed of the propellant supplementary disk and that flame induced that the flame on the whole surface of propellant sample was occurred and combustion was completed with constant burning area. In this study two propellant samples in one experiment is spent and not only ignition simultaneously on each surface of propellant samples but also the timing which ignites from both end side must agree. Acoustic wave which expect to form in the T-Burner ultimately has to be linear wave as the type of stand wave. If the notable difference of ignition time of two propellant samples exist, the propellant sample which ignites first become the high pressure region, or the propellant sample which ignites second form the low pressure region. The pressure gradient induces asymmetry in the tube thus the traveling wave creates. In order not to occur an asymmetry problem, the electric of igniter and physical conditions of T-Burner maintained to be identical at the both end side of the T-Burner. Fig. 5 (a) and (b), respectively, when the ignition failed simultaneously and when the ignition accomplished simultaneously well, are the picture which compares.



(a) Without the ignition supplementary disk



(b) With the ignition supplementary disk

Fig. 5 The simultaneous ignition by the ignition supplementary disk

Result and Discussion

In this research, the propellant is used as a kind of HTPB/AP propellant with Al particle for acoustic stability. To exclude the effect for a particle size, aluminum particles in order of size is contained indiscriminately.

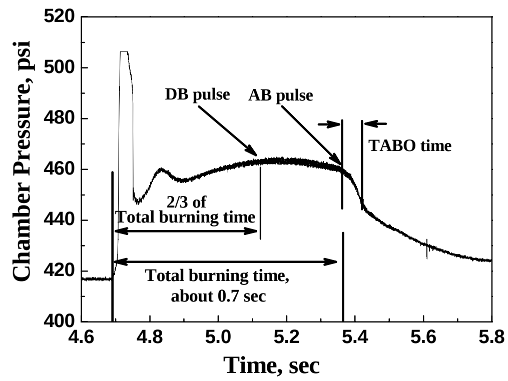


Fig. 6 A total combustion time and an operation timing of the DB/AB pulse

Burning time of solid propellant sample is 0.7 s in the combustion pressure of 460 psi. A point of Operating time of DB pulser made to be fixed at 2/3 of whole combustion time, 0.47 s, and AB pulser operated at completion point of burning, 0.7 s as Fig. 6.

Amplification coefficient of combustion only, α, aluminum-free

In order to exclude the effect of the aluminum particle, for the propellant where the aluminum particle is not entirely contained in sample, this experiment is accomplished. The burning of propellant samples was carried out stably by using ignition supplementary disk and surge tank for DB and AB pulser operation. It is shown in Fig. 7. Figure 8 is the graph for the net fluctuation except the mean pressure of combustion.

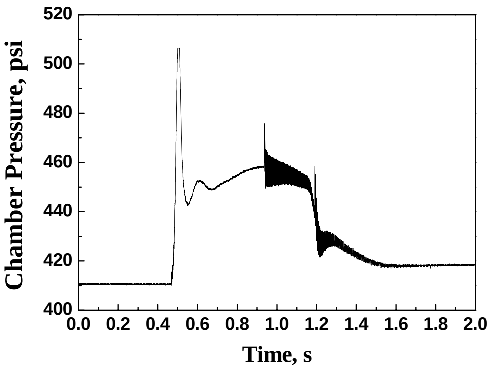


Fig. 7 The combustion pressure trace of aluminum-free solid propellant in the T-Burner

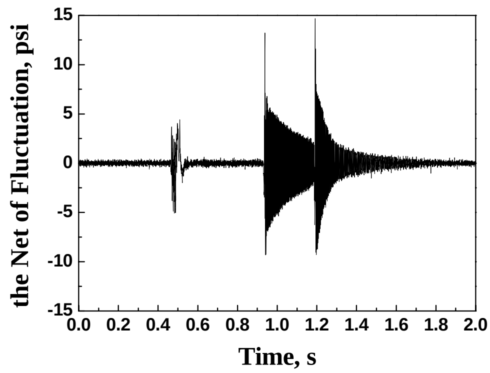


Fig. 8 the Fluctuation of the combustion pressure in the T-Burner

The pressure fluctuation at 0.5 s was generated by the combustion of ignition assistance, it was attenuated rapidly, thus, operating timing of pulser is not affected. For calculation of acoustic attenuation coefficient it separated a pressure data respectively in DB pulses and AB pulse parts. And they were filtered through the low pass filter and the high frequency above 800Hz removed. Fig. 9 is to magnify the parts of DB pulse. By spectral analysis through postprocessing of the pressure data, it shows eigen frequency of 420 Hz as Fig. 10. The largest value is abstracted from a pressure curve, Fig. 9 and then the attenuation coefficient, α_{DB} is calculated as -5.2/s by curve fitting. The effective temperature and speed of sound based on experimental results is considered as 2065 K, 840 m/s, respectively.

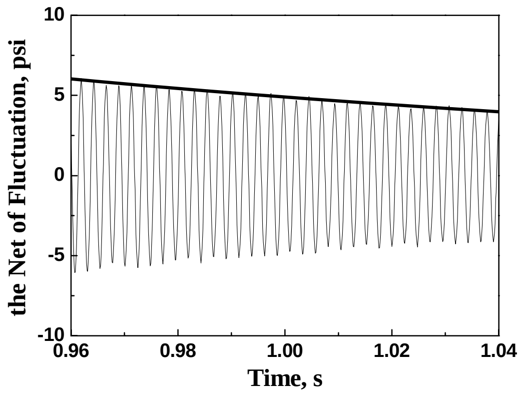


Fig. 9 the Pressure fluctuation by the DB pulse after data postprocessing, filtered by low pass filter, 800 Hz

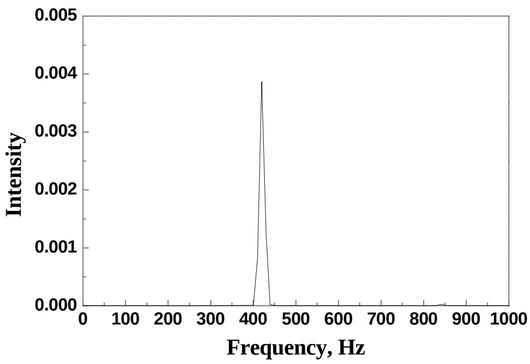


Fig. 10 A spectral Analysis of the pressure fluctuation of the DB pulse part

The part of AB pulse is processed by identical way as the postprocessing of DB pulse. Figure 11 is the graph of the pressure to be result.

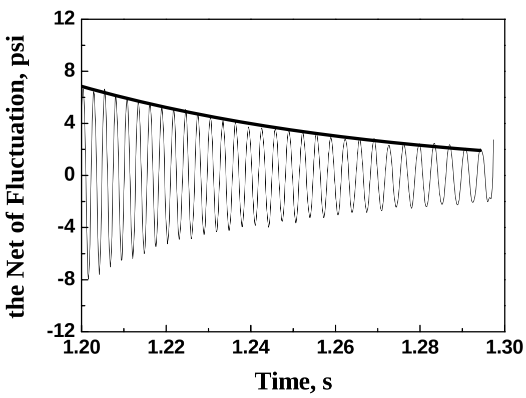


Fig. 11 the Pressure fluctuation by the AB pulse after data postprocessing, filtered by low pass filter, 800 Hz

By spectral analysis, as Fig. 12, the eigen frequency is considered as 312 Hz with having a width. The frequency of the T-Burner is the function of length of combustion chamber. Nevertheless the eigen frequency of AB pulse part is different from the eigen frequency of DB pulse part in the identical length of the T-Burner. Because AB pulse have to operate at the end of combustion exactly in the same conditions of thermodynamic which is not combustion effect but not operate properly. So this difference occurred. Because of decreasing of temperature rapidly by the pressure drop, the frequency is measured smaller than the frequency of DB part. Figure 11 shows that the wavelength comes to be long more and more according to time at latter. It is the reason that the frequency of AB pulse has a larger width than that of DB pulse at the frequency spectrum.

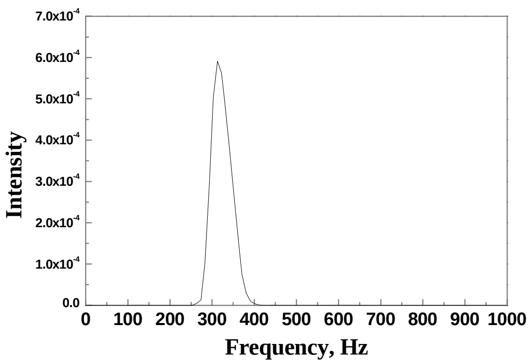


Fig. 12 the Spectral Analysis of the pressure fluctuation of the AB pulse part

The effective temperature of AB pulse part predicted as 1144 K. And the attenuation coefficient, α_{AB} which has system characteristic without combust effect is considered as -13.5. Thus, the amplification coefficient, α which shows the propellant characteristic by combustion effect only, is considered about 8.3 /s which draws out attenuation coefficient of the pressure fluctuation by AB pulses, α_{AB}, from the attenuation coefficient of the pressure fluctuation by DB pulses, α_{DB}.

Amplification coefficient of combustion only, α, aluminum-heavy

In this case, the experiment was attained for propellant including lots of aluminum. The DB pulser and AB pulser were operated at about 26.1 and 26.5 s, respectively. (see Fig. 13) This process is the part of experiment to set TABO (Time After Burn Out) for AB pulser operating. The important point is that the pressure fluctuation which is caused by the pulse is attenuated quite quickly. The attenuation coefficient couldn't get and the pressure fluctuation which was caused by pulser was attenuated rapidly. Generally, there are lots of reasons where solid propellant contains aluminum particle, and two main reasons of them are the role of thrust increasing by high enthalpy and the role of attenuation of perturbation by energy loss. Since the density of liquid aluminum is extremely larger than combustion gas in the combustion chamber, the motion of liquid aluminum is not affected by gas motion.

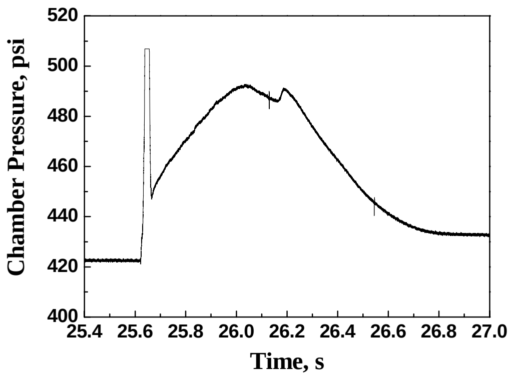


Fig. 13 the Combustion pressure trace of the aluminum-heavy solid propellant in the T-Burner

The damping effect is introduced by kinetic energy loss due to relative motion of between liquid aluminum and combustion gas.[11] Considering the factor that make combustion instability attenuate, it is known that aluminum quantities, 3% of mass ratio is the most effective by literature. In this case, the propellant contained many aluminum particles is considered to avoid combustion instability rather than to increase thrust. This propellant is very stable for combustion instability, thus it can't result any data to calculate combustion characteristic in this experiment.

Conclusion

To examine the effects of aluminum on deactivating the high-frequency instabilities in Al/HTPB solid propellants, the Pulsed DB/AB Method combined with various T-Burner techniques was conducted. With higher concentration of aluminum, fluctuating pressure waves quickly dissipate the wave energy through the gas dynamic interactions between the gas and the Al particle. Acoustics evolutions were not in their wave form, and thus provide no amplification coefficient. In the case of aluminum-free propellant, the amplification coefficient was finite. Addition of aluminum particles into the propellant seems to be advantageous for stabilizing pressure-coupled unstable waves.

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