Springer

Journal of Mechanical Science and Technology 23 (2009) 1112~1117

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-009-0302-y

Measurement of solid propellant burning rates by analysis of ultrasonic full waveforms †

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(Manuscript Received December 6, 2007; Revised April 4, 2008; Accepted April 26, 2008)

Abstract

The measurement of solid propellant burning rates using ultrasound requires the simultaneous acquisition and analysis of ultrasonic signals and pressure data simultaneously in a wide range of pressure values during the process of propellant burning. Recently, this method has been proposed as an effective approach based on an analysis of full waveforms of ultrasonic signals together with a laboratory prototype system in which the proposed approach has been implemented. However, this prototype system had limitations in terms of data processing speed and signal processing procedures. To overcome such limitations, in the present study, we develop a dedicated, high speed system that can acquire ultrasonic full waveforms and pressure data up to 2,000 times per second. Our system can also estimate the burning rate as a function of pressure using a special software based on ultrasonic full waveform analysis. This paper describes the approach adopted in this high speed system, along with the burning rate measurement results obtained from three propellants with different burning characteristics.

Keywords: Ultrasonic measurement; Burning rate; Solid propellant; Time-of-flight

1. Introduction

The ballistic behavior of a solid propellant rocket is strongly influenced by the burning rates of the solid propellant. As such, it is very important to accurately measure its burning rate. Given that the internal pressure of a solid propellant rocket increases drastically during propulsion, it is also necessary to measure the burning rate in a wide range of pressure values. For this purpose, a strand burner method is widely adopted as a standard technique [1]. However, the strand burner technique only measures a specific burning rate under a constant pressure, so it requires a number of measurements to determine the burning rates at many different pressures. This method is therefore costlier and more time consuming.

To overcome this challenge, proposals have been made regarding ultrasonic techniques that measure the burning rates as a function of pressure in a single test performed under a constant volume condition [2]. Fig. 1 schematically shows a typical ultrasonic test setup for measuring the burning rates of a solid propellant. In this setup, a burning chamber often called a “closed bomb” contains a piece of solid propellant which is firmly attached to a solid couplant (usually made of resin) enclosed by a cylindrical metal bushing. A normal beam ultrasonic transducer is attached to the solid couplant placed outside of the closed bomb, which then radiates ultrasonic pulses to the couplant to receive two reflected signals:1) the “interface echo” produced at the interface between the solid couplant and the propellant and 2) the “surface echo” generated

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† This paper was recommended for publication in revised form by Associate Editor Dae-Eun Kim

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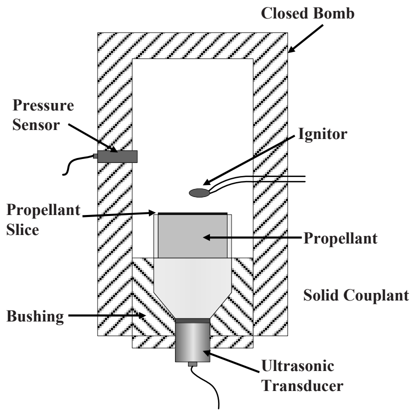


Fig. 1. A schematic representation of the ultrasonic testing setup for measuring the burning rates of a solid propellant sample mounted in a closed bomb.

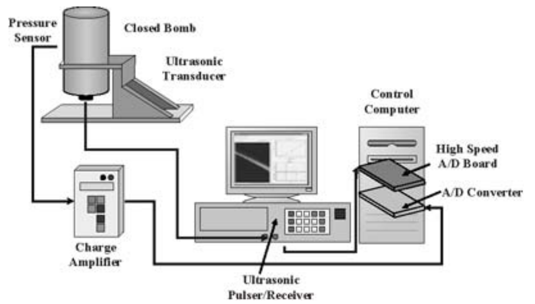


Fig. 2. A schematic representation of an ultrasonic full waveform signal and pressure data acquisition and analysis system developed in the present study.

from the end of the solid propellant sample being investigated. By measuring the time-of-flight between these two reflected signals (i.e., the interface echo and the surface echo) it is possible to estimate the remaining length of a solid propellant during the burning process. In addition, a pressure gauge is also inserted to the closed bomb in order to measure the internal pressure of the closed bomb which varies due to gases produced during propellant burning. Therefore, using this setup, it is possible to measure the remaining length of a solid propellant at various pressure values during the burning process. The data acquisition rate will be controlled by a hardware and software specification of the measurement system.

To increase the data acquisition speed, one of the widely adopted techniques is tracking the arrival time of returning ultrasonic signal using dedicated hardware circuits [3]. However, since most hardware signal tracking circuits search for only a single peak at a time, carrying out three different tests (a pre-test, a burning test and a post test) is required in order to determine the burning rates using those measurement systems [4]. Both the pre-test and the post-test are carried out to determine the variation of the ultrasonic wave speed of the solid propellant according to pressure. The pre-test is a pressurization test performed before the burning test. However, given that the wave speed of the couplant also varies according to pressure, the time-of-flight information acquired from the pre-test also contains the variations caused by the couplant. To compensate for this influence, the post-test is carried out after the actual burning test using the remaining couplant. This test should be performed when the temperature of the remained couplant drops down to a specified temperature, since the temperature itself also has a strong effect on the wave speed. Usually, it can be carried out after a couple of hours after the burning test. For this reason, burning rate estimation approaches based on peak detection usually takes more than two hours due to the necessity of conducting a post-test.

This time-consuming post-test can be eliminated by acquisition and analysis of ultrasonic full waveform signals in the pre-test and the burning test. Recently, we have developed a laboratory prototype system that can acquire 800 sets of ultrasonic full waveforms and pressure data in a second [5]. However, this prototype system had limitations in its data acquisition and processing capabilities. In fact, to use this system one has to carry out a series of data post-processing which is also tedious and time consuming.

To overcome such limitations, we develop in this study a dedicated, high speed system that can acquire ultrasonic full waveforms and pressure data up to 2,000 times per second. Our proposed system can also estimate the burning rate as a function of pressure using a special software based on ultrasonic full waveform analysis. This paper describes the approach adopted in this high speed system, along with the burning rate measurement results obtained from various propellants with different burning characteristics.

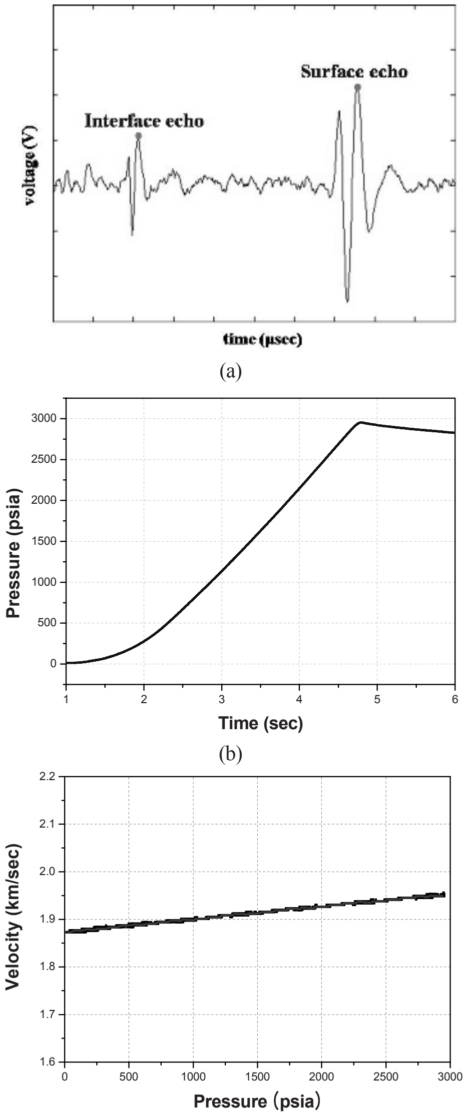
2. Ultrasonic burning rate measurement system

Fig. 2 shows the high speed ultrasonic full waveform acquisition and analysis system developed in the present work. This system, which aims to determine the solid propellant burning rates as a function of pressure, consists of four major parts: 1) a closed bomb that can be pressurized up to approximately 4,000 psi; 2) an ultrasonic signal acquisition system including a normal beam ultrasonic transducer, an ultrasonic pulser/receiver, a high speed A/D conversion board (with a sampling rate of 100 MHz) and connecting cable; 3) a pressure data acquisition system composed of a pressure gauge, a charge amplifier and A/D converting board (with a sampling rate of 1 MHz); and 4) a control computer which uses a specially developed application software for acquisition and analysis of ultrasonic full waveforms and pressure data (in the pre-test and the burning test) in order to invoke the burning rate as a function of pressure. Due to the fact that the thermal profile has no significant effect on the burning rate, the pressure-induced stress effect (known as the "pressure effect") has to be taken into account in order to correct the burning rate values [6]. The major hardware components, such as the ultrasonic pulser/receiver and the A/D boards, were carefully chosen so that the total system can acquire ultrasonic full waveforms and pressure data up to 2,000 times in a second. The special application software developed in the present work can be divided into two modules: the data acquisition module and the signal analysis module. The data acquisition module controls the hardware components in order to acquire ultrasonic signals and pressure data in a synchronized fashion. The signal analysis algorithms explained in the following section have been implemented in the analysis program in order to execute the algorithms in an automated manner.

3. Signal analysis algorithms

The signal analysis algorithms established in the present work can be divided into two parts: 1) for estimating ultrasonic wave speed as a function of pressure from the pre-test, and 2) for determining solid propellant burning rate at many different pressure values from the burning test.

In order to estimate the ultrasonic wave speed in the solid propellant at a certain pressure, a set of ultrasonic full waveform signal and pressure data was acquired instantaneously in the pre-test, in which the closed bomb became increasingly pressurized by nitrogen gas. Then, the time-of-flight between the interface echo and the surface echo was automatically measured from the ultrasonic full waveform signal (acquired at a specific time) by the software in which a cross-correlation analysis was implemented.



(c)

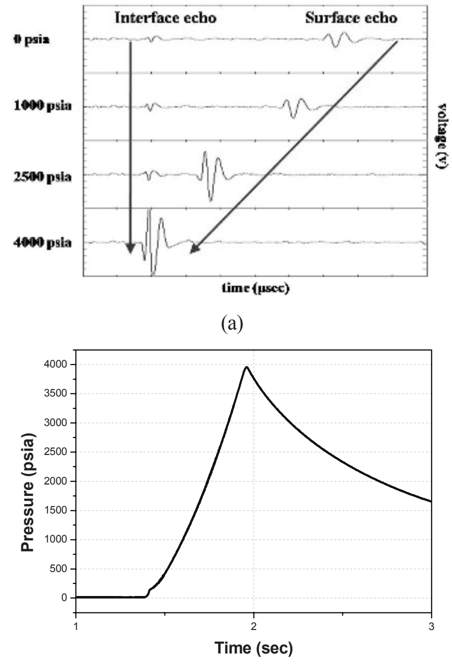
Fig. 3. Estimation of the velocity-pressure curve of the Type I solid propellant from the pre-test data: (a) a sample ultrasonic waveform acquired at the ambient pressure, (b) the pressure-time curve due to pressurization, and (c) the invoked velocity-pressure data and the curve-fitted line (solid).

From observation, it is apparent that the arrival times of both the interface echo and the surface echo vary according to varying pressure levels. The arrival time variation for the interface echo is caused by the ultrasonic wave speed variation in the couplant, while that for surface echo is influenced by the velocity variations occurred in both the couplant and the solid propellant. In this approach, however, the influence of the couplant can be eliminated naturally since one is measuring the time-of-flight between two echo signals. By assuming that the length of the solid propellant does not change due the pressurization by nitrogen gas, one can estimate the ultrasonic wave speed at the specific time by dividing the measured time-of-flight value by two times of the original length of the solid propellant under interrogation. Given that the pressure data at the specific time is also monitored by the acquisition system, one can identify the wave speed at that specific pressure by simply replacing the measured time data by the measured pressure value at that specific moment.

Fig. 3 shows an example of the invoked ultrasonic wave speed according to the pressure for a Type I solid propellant, together with a sample ultrasonic waveform acquired at ambient pressure (before pressurization) and the pressure-time curve obtained during the pressurization in the pre-test. As discussed previously, the velocity-pressure curve that can be invoked from the pre-test data is discrete in pressure, although it looks continuous due to high speed data acquisition. Furthermore, this discrete velocity-pressure data is contaminated by random noise caused by various sources such as quantification error. Therefore, it would be necessary to make the curve smoother using a data-fitting scheme. In this specific example, a polynomial curve fitting has been adopted in order to estimate a velocity-pressure function that can describe the discrete velocity-pressure data in a smooth and continuous manner. This curve-fitted line is also presented in Fig. 3.

The burning rates of the solid propellant at many different pressure values can be determined through an analysis of data acquired from the burning test. Similar with the pre-test, a set of ultrasonic signal and pressure data is acquired in the burning test. Fig. 4 shows a set of sample waveforms acquired at various pressure values, together with the pressure-time curve obtained from a burning test of Type I solid propellant. As shown in this figure, the time-of-flight between the interface echo and the surface echo decreases according to the increase of pressure in the closed bomb due to propellant burning.

From the results shown in Fig. 4, it is possible to estimate the remaining length of the solid propellnt while burning. Meanwhile, the remaining length at a certain pressure can be calculated by multiplying two elements: a) the time-of-flight between the interface echo and the surface echo measured at that moment; and b) half of the ultrasonic wave speed of the solid propellant determined (at the same pressure) from the pre-test results as shown in Fig. 3. Once the remaining length of the propellant is available, the burnt length can also be calculated very easily by subtracting the remaining length from the original length of the propellant sample. Then, the burning rate of the propellant at that specific pressure can be estimated by differentiation of the burnt length with respect to time.



(a)

(b)

Fig. 4. A sample burning test result of Type I solid propellant, (a) sample ultrasonic waveforms at various moments, and (b) the pressure-time curve obtained during the burning test.

Fig. 5 shows an example of the invoked burning rate of the Type I solid propellant according to the algorithms discussed. It is noteworthy that the burning rate data presented in Fig. 5 are discrete in pressure and are heavily contaminated by various sources of errors, especially including those related to numerical differentiation. Therefore, it is necessary to carry out proper data smoothing operation. One of the efficient ways to do so is through the process of applying a polynomial curving fitting to the burnt length of the propellant (i.e., the data before numerical differentiation), rather than applying it to burning rate. One of the obvious advantages of this approach is that errors due to numerical differentiation can be minimized. This data smoothing approach has been ap-

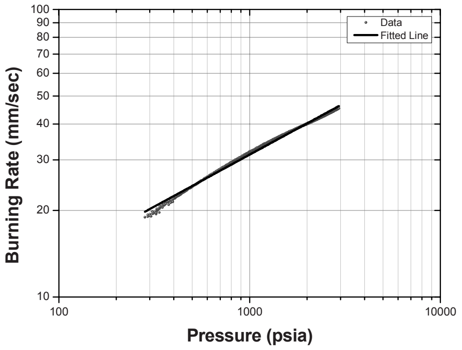


Fig. 5. A sample of burning rate determination for the Type I solid propellant. Solid line – curve fitted line, Dotted line – measured discrete data.

(a) (b) (c)

Fig. 6. Photos of solid propellant specimens: (a) Type I, (b) Type II, and (c) Type III.

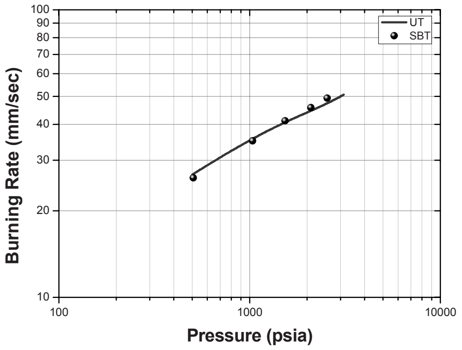


Fig. 7. Results of burning rate measurement for the Type I solid propellant. Solid line: ultrasonic full waveform analysis method; Solid dots: measurement by a strand burner method.

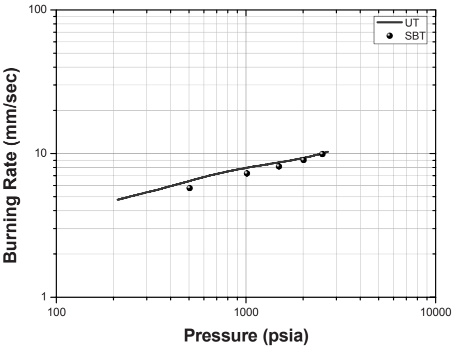


Fig. 8. Results of burning rate measurement for the Type II solid propellant. Solid line – ultrasonic full waveform analysis method, Solid dots – measurement by a strand burner method.

plied to the Type I solid propellant in the present study, and the curve fitted line is also presented (as the solid line) in Fig. 5. As shown in the figure, the curve-fitted line effectively represents the behavior of the measured, discrete burning rate data.

4. Results for various solid propellants

The ultrasonic full waveform analysis approachdiscussed in the previous section has been applied to three solid propellants (as shown in Fig. 6) with different burning characteristics. Type I and Type II are composite AP-Al types of propellants with different weight percentages of aluminum, while Type III is double-based composite propellant. The web distance and diameter of the propellants are 20 mm and 25 mm, respectively.

Fig. 7 shows the results obtained from the Type I propellant. In this figure, the ultrasonic measurement result is compared to that obtained by a strand burner technique. As can be seen from the figure, the ultrasonic measurement agrees very well to that of the strand burner, showing 1.64% of relative error at a pressure value of 1,000 psi.

Fig. 8 shows similar results obtained from the Type II propellant that has slower burning rates compared to the Type I propellant. As presented in this figure, however, the ultrasonic measurement result shows a relatively large discrepancy from the results obtained through the strand burner technique. The relative error to the strand burner value is 9.63% at the pressure of 1,000 psia.

Fig. 9 shows similar results obtained from the Type III propellant which has a “dark zone” in the burning rate. This dark zone signifies that there is a local decrease in the burning rate along with the increase of pressure. As shown in Fig. 9, however, the ultrasonic measurement successfully describes the dark zone behavior of this propellant, demonstrating the strong capability of the current signal analysis approach. However, one can see relatively large discrepancies with regard to the strand burner results at the high pressure region.

We believe that the possible sources of the discrepancies could be various factors such as the attenuation

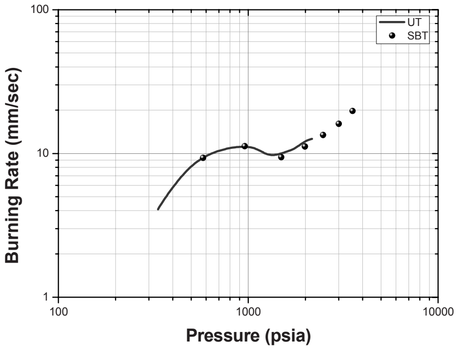


Fig. 9. Results of burning rate measurement for the Type III solid propellant. Solid line: ultrasonic full waveform analysis method; Solid dots: measurement by a strand burner method.

of ultrasonic waves in the solid propellants. Currently, we investigate the effect of the attenuation of ultrasound on ultrasonic burning rate measurement [7].

5. Conclusions

In the present study, we have proposed an ultrasonic full waveform analysis approach that can efficiently identify the burning rates of a solid propellant in a wide range of pressure values. Furthermore, we have also developed an ultrasonic measurement system in which the proposed approach has been implemented in a dedicated application software. In order to evaluate the proposed method's performance with regards to various propellants, we have applied the proposed approach to three types of solid propellants that show different burning characteristics. The promising results obtained in the present study demonstrate high potential and capability of the proposed approach and the developed system.

Acknowledgment

The authors would like to thank the Defense Acquisition Program Administration and the Agency for Defense Development for the financial support provided by both institutions.

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