



Improved method of measuring pressure coupled response for composite solid propellants



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ABSTRACT

Pressure coupled response is one of the main causes of combustion instability in the solid rocket motor. It is also a characteristic parameter for predicting the stability. The pressure coupled response function is usually measured by different methods to evaluate the performance of new propellant. Based on T-burner and “burning surface doubled and secondary attenuation”, an improved method for measuring the pressure coupled response of composite propellant is introduced in this article. A computational fluid dynamics (CFD) study has also been conducted to validate the method and to understand the pressure oscillation phenomenon in T-burner. Three rounds of tests were carried out on the same batch of aluminized AP/HTPB composite solid propellant. The experimental results show that the sample propellant had a high response function under the conditions of high pressure (~ 11.5 MPa) and low frequency (~ 140 Hz). The numerically predicted oscillation frequency and amplitude are consistent with the experimental results. One practical solid rocket motor using this sample propellant was found to experience pressure oscillation at the end of burning. This confirms that the sample propellant is prone to combustion instability. Finally, acoustic pressure distribution and phase difference in T-burner were analyzed. Both the experimental and numerical results are found to be associated with similar acoustic pressure distribution. And the phase difference analysis showed that the pressure oscillations at the head end of the T-burner are 180° out of phase from those in the aft end of the T-burner.

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1. Introduction

Combustion instability in solid rocket motors is a thorny problem that is perplexing to the researchers since World War II. Its fundamental characteristics are the periodic oscillations of pressure, burning rate, and thrust [1]. It can be induced by many factors, such as pressure coupled response, velocity coupled response, distributed combustion, vortex shedding, etc. [2–4]. Generally, the propellant combustion process contributes nearly 40 percent of the acoustic energy to the combustion instability. This effect is academically called pressure coupled response and is mathematically defined as the ratio between the perturbed burning rate over the mean burning rate and the perturbed pressure over the mean chamber pressure. It is a characteristic parameter of the solid propellant that is used to estimate the stability of the solid rocket motor and to evaluate the performance of new propellant. Since 1950s, researchers have been working on the combustion response theory, and gradually yielded analytical solution for the pressure coupled response. Culick [5] once made an excellent review on the

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expressions of response function. Nowadays, the pressure oscillations become so common in many types of combustion systems that numerous studies have been carried out to suppress combustion oscillations, either passive or active techniques are used to break the coupling between unsteady heat release and acoustic waves, based on a Rijke tube [6–9]. However, the burning conditions of solid propellant in rocket motors are high pressure and temperature, which is different from Rijke tube. The pressure coupled response can be affected by the chamber pressure, propellant temperature, oscillation frequency, propellant formulation, etc. The existing analytical method is not able to accurately determine the value of the propellant pressure coupled response function. Therefore, experiment is the preferred method to study the pressure coupled response. Till now, there have been developed different experimental methods to measure the pressure coupled response, such as T-burner [10], rotary valve [11], the microwaves [12], magnetic flow meter method [13], etc., in which T-burner is a mature and widely used method. The experimental techniques involved in this application are well described by Coates [14]. Based on T-burner, the pressure coupled response was tested by many researchers to evaluate the performance of new propellants [15,16]. Sun [17] had proposed an improved algorithm for the measurement of the pressure coupled response, which was called “burning surface doubled and secondary attenuation”. In his method, the attenuation constants were measured with different burning surfaces under the condition of the controlled chamber pressure. His method increased the accuracy of measurement for the response function. On the basis of this method, Wang and his co-workers [18–20] carried out the experimental work on more than 20 kinds of double-base propellant. They comprehensively summarized the pressure coupled response characteristics of the double-base propellant under different frequencies and pressures. Most of the research work is focused on the double-base propellant, because this kind of propellant is prone to self-sustained oscillations. Nowadays, the high energy aluminized AP/HTPB composite propellant is widely used in the solid rocket motors. The combustion instability phenomenon once again attracted the attention of researchers. However, the composite propellant cannot spontaneously arouse pressure oscillations in the T-burner. Furthermore, even if self-excited oscillation occurs, the oscillation pressure can be easily damped. Therefore, the traditional T-burner method cannot provide sufficient information to estimate the response function for composite propellant. In order to overcome this drawback, Oberg [21] proposed a pulsed T-burner technique. The T-burner was pulsed by the ignition system to excite transient pressure oscillations that can be used to estimate the pressure coupled response function. Blomshield [22,23] had studied the pressure coupled response of composite propellant via a “pulsed during burn after burn” technique, which was an improved pulsed T-burner technique. Data were obtained by pulsing the T-burner during the propellant burn and after burnout. He had systematically studied the effect of the AP size, chamber pressure, burning rate and frequency on the pressure coupled response and provided some important “rule of thumb” methods for estimating response functions for future propellants.

The chamber pressure can greatly affect the pressure coupled response of propellants. For the purpose of eliminating the effect of mean chamber pressure on the pressure coupled response function, the traditional T-burner experimental system has an external pressure control valve at the end of the nozzle so as to keep the pressure constant in the T-burner chamber. The pulsed T-burner technique provides an ingenious way to measure the pressure coupled response function for composite propellant, and excludes the impact of mean pressure. However, it has complex external pulse equipment. Besides, the first pulse can easily exert on the T-burner during the propellant burn. But the second pulse is difficult to control, because it should be strictly exerted on T-burner after the propellant burnout.

In this work, the present authors have developed a new way to measure the pressure coupled response function. It is also a pulsed T-burner technique, but the experimental setup is greatly simplified. The external pulse equipment is replaced by a newly designed grain structure that self-contains two pulses. At one end of the T-burner, black powder is added both in the middle and end of the sample propellant to pulse the pressure oscillations, while the opposite end is only placed with sample propellant free of black powder. According to the attenuation constants after the two pulses, the pressure coupled response of the propellant can be calculated via the “burning surface doubled and secondary attenuation algorithm”. Based on this experimental setup and data analysis algorithm, three rounds of tests were carried out on the same batch of aluminized AP/HTPB composite solid propellant. The value of the pressure coupled response can be regarded as the evaluation criteria for the sample propellant.

Computational fluid dynamics (CFD) has been widely used in the study of combustion instability phenomenon, especially in the Rijke tube [24,25]. Inspired by the successful numerical applications, we applied the commercial CFD code FLUENT6.3[®] to simulate the pressure oscillations in a two-dimensional T-burner model, which has the same size with the experimental setup. The numerical simulation work is carried out to validate our improved method in this paper. Furthermore, the CFD tool can help to understand the pressure oscillation phenomenon in the T-burner.

Lastly, acoustic distribution in T-burner is analyzed. Comparison is made between experimental and numerical results. And the acoustic pressure phase differences between the head end and aft end of the T-burner are analyzed as well in this work.

2. Experimental system and theory

2.1. Experimental system

The experimental setup consists of power system, data acquisition system, ignition control system, display computer and the T-burner. The schematic of experimental setup is shown in Fig. 1.

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