Experimental research on ultrasonic A-scan testing technology of composite solid propellant

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Abstract—To explore the application and development of ultrasonic non-destructive testing technology in composite solid propellant materials, the theory is combined with the principle and method of ultrasonic non-destructive testing technology and the material characteristics of composite solid propellant; Based on ultrasonic A-scan, the experimental testing of propellant grain with multiphase structure, complex properties and high attenuation was carried out using pulse reflection method and penetration method. For the testing system with probe emission frequency of 1 MHz and gain adjustable range of 60 dB, the thickness of propellant grain is recommended to be 10 ~ 50 mm for the pulse reflection method to effectively observe the first bottom echo and the second bottom echo, and the thickness of propellant grain is recommended to be less than or equal to 100 mm for the penetration method to effectively observe the transmission waveform. The coupling modes of ultrasonic testing technology are further analyzed, and the effect test is carried out. In addition, based on the pulse reflection method of direct contact coupling, the sound velocity of propellant grain is measured with probes with different frequencies. The results show that the higher the probe frequency is, the smaller the sound velocity of propellant grain is.

1. Introduction

Nondestructive testing technology can protect the basic situation of the test object to the greatest extent. The most common nondestructive testing methods are ultrasonic testing, radiographic testing, magnetic particle testing, and liquid penetrant testing. Compared with other non-destructive testing technologies, ultrasonic testing technology has the unique advantages of high testing efficiency, low testing cost, and no harm to the human body. It is often used for the testing, evaluation, and monitoring of material properties: Li Fen[1] and others believe that the testing of sound velocity can quantitatively evaluate the early damage degree of asphalt concrete pavement; Ren Jianbo[2] and others applied ultrasonic testing technology to the testing of butt circumferential welds between steam generator barrel and cone in nuclear power plant; Li Li[3] et al. Used ultrasonic synthetic aperture focusing imaging testing method to improve the imaging effect of an ultrasonic transducer in detecting coal rock interface.

However, there are only a few relevant reports on the testing and evaluation of composite solid propellant grain properties based on ultrasonic nondestructive testing technology: E.C. Johnson[4] studied the feasibility of using ultrasonic measurement of propellant mechanical properties to monitor the condition and curing degree of propellant. The research results show that the change of peak frequency data is related to the curing degree. On this basis, I carried out the experimental research on the variation law of ultrasonic parameters of HTPB solid propellant under the condition of high-temperature accelerated aging. It was found that with the increase in high-temperature aging time, the
ultrasonic longitudinal wave velocity of propellant grain generally showed an upward trend and the
attenuation coefficient generally showed a downward trend [5]. At present, the application of composite
solid propellant with ultrasonic nondestructive testing technology is still focused on the study of the
bonding interface between shell and charge [6-8]. At the same time, the research on the performance
state of composite solid propellant mostly adopts the method of mechanical property test. This method
not only needs to prepare a large number of samples, but also is destructive, easy to cause certain
economic losses and has certain limitations [9-11].

Based on the principle and method of ultrasonic nondestructive testing technology, aiming at the
performance testing of composite solid propellant grain, this paper focuses on the ultrasonic A-scan
testing experiment of propellant grain, studies the testing means and testing effect of propellant grain,
and the variation law of sound velocity of propellant grain with testing frequency.

2. Method and principle

2.1 Principle of ultrasonic testing technology
The pulse reflection method and penetration method are two typical testing methods in the principle of
ultrasonic testing technology. The pulse reflection method is to transmit the pulse wave into the test
piece through the ultrasonic transmitting probe, and detect the performance or defects of the test piece
according to the reflected echo received by the receiving probe; The penetration method is to transmit
the pulse wave or continuous wave into the tested piece through the ultrasonic transmitting probe and
detect the performance or defects of the tested piece according to the transmitted wave received by the
receiving probe. The principles are shown in Fig.1 and Fig.2. T represents the initial wave, F
represents the defect echo, and B represents the bottom echo, P represents the transmitted wave.

Fig.1 Schematic diagram of testing principle of pulse reflection method

Fig.2 Schematic diagram of testing principle of penetration method

2.2 Composite solid propellant
Composite solid propellant grain is a kind of viscoelastic material with elastic and viscous deformation
mechanisms; It is a multiphase mixture with high polymer as a matrix and mixed with oxidant, metal
fuel, and other components. It has better low-temperature mechanical properties, higher energy characteristics, and more accurate ballistic properties \cite{12}. Due to the changes of multiphase structure composition and complex performance state of composite solid propellant, the propagation process of ultrasonic wave in propellant grain will be greatly hindered, resulting in great attenuation of ultrasonic energy. For the ultrasonic testing of composite solid propellant grain, it is very important to explore suitable testing methods.

3. Experiment and Discussions

3.1. Testing of pulse reflection method and penetration method

The experimental object is the sample of composite solid propellant grain, the size is about mm; The experimental equipment adopts the self-developed 8077PR ultrasonic testing system, the ultrasonic probe frequency is 1 MHz, the wafer diameter is 20 mm, and the special colloidal coupling agent for ultrasonic is used to provide the coupling layer.

Pulse reflection method: place the working probe on the sample surface of the propellant grain, apply colloidal coupling agent between the probe and the sample surface, detect the thickness of 25 mm, collect and observe the waveform signal, and the results are shown in Fig.3. Penetration method: the transmitting probe and receiving probe are respectively placed on two parallel faces of the propellant grain sample, the colloidal coupling agent is applied between the probe and the sample surface, the two probes are aligned so that the center point is about the same straight line, the testing thickness is 25 mm, and the waveform signal is collected and observed, and the results are shown in Fig. 4.

![Fig.3 Testing of solid propellant grain by Pulse reflection method](image1)

![Fig.4 Testing of solid propellant grain by penetration method](image2)
the propellant grain is thin, the first bottom echo may fall in to the initial wave, resulting in no resolution; If the propellant grain is thick, the bottom echo may not be observed effectively. Therefore, the recommended propellant thickness is 10–50 mm. The transmission wave signal can be received by the penetration method without initial wave interference. The propellant thickness is recommended to be less than or equal to 100 mm.

3.2. Coupling conditions of ultrasonic testing

Ultrasonic wave will produce strong reflection on the heterogeneous interface with large difference in acoustic impedance, which greatly reduces the transmission effect of ultrasonic wave. Therefore, to improve the transmittance of ultrasonic penetration into the test piece, conventional ultrasonic generally needs to fill the coupling agent between the working probe and the surface of the test piece. This section mainly explores three coupling methods of ultrasonic testing technology, namely contact method coupling, water immersion coupling and air coupling. Based on the testing principle of penetration method, the coupling process is shown in Fig. 5.

(a) Namely contact method coupling (b) Water immersion coupling (c) Air coupling

Fig. 5 Coupling conditions of ultrasonic testing

The contact method is adopted for coupling, the coupling agent is generally colloid or oil, and the working probe is in direct contact with the surface of the propellant sample; The ultrasonic signal energy observed by this method is strong, but the signal amplitude is sensitive to the coupling pressure. If the coupling pressure changes slightly during the testing process, it may cause drastic changes in the waveform. The surface of the specimen is required to be flat and smooth and not too rough. Using water immersion coupling, the working probe is not in direct contact with the surface of the propellant sample, and water is filled between them; This method has good coupling condition stability, stable ultrasonic signal waveform, and good reproducibility, but the material properties are not sensitive to water. Air coupling is a new ultrasonic testing technology, which adopts air coupling, and the working probe is not in direct contact with the surface of the propellant sample; This method has the same advantages as the water immersion method, that is, the ultrasonic signal is stable, the reproducibility is good, and the signal amplitude is not affected by the coupling pressure. However, the air coupling probe is made of special materials. Due to the limitation of material properties, the energy conversion efficiency is low, higher excitation voltage is required, and special signal amplification equipment is required.

3.3. Measurement of sound velocity at different emission frequencies

Based on the direct contact coupling ultrasonic pulse reflection method, the sound velocity of propellant grain was measured by probes with different frequencies. To eliminate the influence of the structure of different parts of the grain on the sound velocity, the measured results of the sound velocity at three positions are taken, and the average value is calculated as the sound velocity value at the current probe frequency. The data results are shown in Table 1. It is found that the higher the frequency of the ultrasonic probe, the smaller the sound velocity of the propellant grain.
TABLE 1. Sound velocity data results of different probe frequencies

| Frequency/MHz | Position 1 | Position 2 | Position 3 | Average sound velocity/km·s⁻¹ |
|---------------|------------|------------|------------|-----------------------------|
| 0.5           | 2.108      | 2.083      | 2.083      | 2.091                       |
| 1.0           | 1.978      | 1.970      | 1.934      | 1.961                       |
| 1.5           | 1.949      | 1.944      | 1.913      | 1.931                       |
| 2.0           | 1.927      | 1.909      | 1.800      | 1.800                       |

4. Conclusion
In this paper, by combining the theory with the principle and method of ultrasonic nondestructive testing technology and the material characteristics of composite solid propellant grain, the ultrasonic testing means, coupling mode, and sound velocity measurement of propellant grain are experimentally studied, and the following conclusions are obtained:

1) Both pulse emission method and penetration method can be used to detect the performance state of propellant grain. The pulse reflection method is to effectively observe the first bottom echo and the second bottom echo. The thickness of propellant grain is recommended to be 10 ~ 50 mm. The penetration method is to effectively observe the transmission waveform. The thickness of propellant grain is recommended to be less than or equal to 100 mm.

2) Direct contact coupling, water immersion coupling, and air coupling can be used for ultrasonic signal testing of propellant grain. The direct contact coupling is easily affected by the coupling pressure and interferes with the waveform amplitude, and has certain requirements for the surface smoothness of the sample; The waveform stability of water immersion coupling is good, but it is not suitable for water-sensitive materials; Air coupling can avoid the disadvantages of direct contact coupling and inherit the advantages of water immersion coupling, but its material is special and its use cost is high.

3) Based on the pulse reflection method of direct contact coupling, the sound velocity of propellant grain decreases with the increase of transmitting probe frequency.

Acknowledgments
The authors acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 11772352).

References
[1] Li F, Shen C W, Li Y X, et al. (2006) Research on asphalt concrete flaw testing based on ultrasonic testing technology [J] Journal of Wuhan University of Technology (traffic science and Engineering Edition),02: 293-296.
[2] Ren J B, Sun J W, Xu Y N, et al. (2018) Research on ultrasonic testing technology for cone weld of steam generator in nuclear power plant [J] Nuclear power engineering, 2018,39 (4): 83-86 DOI:10.13832/ j. jnpe. 04. eighty-three.
[3] Li L, Wei W, Xia W. (2018) Research on ultrasonic imaging testing of coal and rock based on synthetic aperture focusing technology [J] Journal of China University of mining and technology, 47 (04): 727-734.
[4] Johnson E C, Pollchik J D. (1993) An Ultrasonic Testing Technique for Monitoring the Cure and Mechanical Properties of Polymeric Materials[J].22 August.
[5] Li J, Huang L C, Ai C A, et al. (2021) “Study on the variation law of sound velocity during aging of composite solid propellant,” the 38th Annual Academic Meeting of solid rocket propulsion Professional Committee of China Aerospace society 2021: Zunyi, Guizhou, China. 1205.
[6] Wang Z B, Jin Y. (2003) Ultrasonic testing technology for multi-interface debonding of composites [J] Journal of Taiyuan Normal University, 2 (01): 45-47.
[7] San Emeterio J L, Ramos A, Pardo E, et al. (2008) Ultrasonic pulse propagation in bounded three-
layered structure[J]. Acoustics, 94(9):4639-4644.

[8] Ai C A, Cai X F, Zhao W C, et al. (2011) Three-dimensional graphic reconstruction of ultrasonic C-scan testing of bonded structures [J] Machine tools and hydraulics, 39 (13): 80-83.

[9] Chang L, Yu Y F, Zhang Y H, et al. (2011) Aging fracture performance test of HTPB propellant [J] Propulsion technology, 32 (04): 564-568.

[10] Cheng J M, Li J X, Hou X, et al. (2017) Effect of pre strain on aging dynamic mechanical properties of HTPB propellant [J] Journal of Northwest University of technology, 35 (06): 961-966.

[11] Liu C, Wang Z J, Qiang H F, et al. (2020) Thermal aging properties of HTPB propellant under low temperature dynamic quasi biaxial tensile loading [J] Journal of Astronautics, 41 (03): 353-361.

[12] Rothon R. (1996) Particulate-Filled Polymer Composites[J]. Polymer Testing, 15(4):397.