Review of Research Process and Application of Acoustic Wave Testing Technology for Rock

Zhen-guo Xing 1,2,3*, Yunlan He1,2, Wenfeng Du1,3 and Jie Fang1,2,3

1 State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology(Beijing), Beijing, 100083, China
2 State Key Laboratory of Water Resource Protection and Utilization in Coal Mining, National Energy Group, Beijing, 100011, China
3 College of Geoscience and Surveying Engineering, China University of Mining and Technology(Beijing), Beijing, 100083, China

*Corresponding author’s e-mail: TSP1600201046@student.cumtb.edu.cn

Abstract. The properties of rock medium directly affect geological exploration and geotechnical bridge and tunnel engineering, rock acoustic testing technology has become the mainstream technology of rock physical property test because of its many advantages. The study of rock acoustic testing technology is helpful to further understand the characteristics of rock, and then find out the influence rule of rock physical properties with multi parameters, and better serve engineering practice. On the basis of investigating a large number of relevant documents, this paper systematically summarizes and expounds the rock sound wave testing technology, principle and application and research progress, and makes shallow thinking on the research direction and Prospect of the technology. Pointed out that the basic fields such as testing equipment and technical conditions are relatively weak in China, the rock physics model with wide applicability is still the main research target.

1. Introduction

Rock acoustic wave testing technology has made great progress through the 50a development. It indirectly reflects rock’s physical, mechanical and structural properties by measuring the acoustic parameters of sound waves after sound waves penetrate rock or rock mass. This technology has characteristics such as simple, fast, economical and non-destructive, which has attracted extensive attention from the engineering community at home and abroad. It has been widely used in geology, hydropower, energy, transportation, construction and other industries [1-3].

Domestic and foreign researcher have carried out many theoretical and experimental research work on rock acoustic properties, which constrained in the complexity of rock media itself, the uncertainty of experimental process and the method of acoustic signal processing methods. And it is a long way to go to promote the wider application of rock acoustic testing technology [2-4]. To systematically understand the research progress of rock acoustic wave testing technology, this paper summarizes and expounds the rock acoustic wave testing technology, principle, application and research progress based on many domestic and foreign literatures and summarizes the main problems of this technology.
2. Rock acoustic wave testing technology

Rock is a heterogeneous body composed by various rock-forming minerals with structural defects. Its physical and mechanical properties depend on mineral composition, degree of cementation and development of pores and fissures. The interaction and mutual interference of the rock solid skeleton and the pore fluid on the microscopic scale makes the propagation of the elastic wave in the fluid-saturated porous medium significantly different from the ideal elastic medium [2-6].

At the beginning of the 20th century, Turkish soil mechanic Toksaz first explained the basic concepts of pore fluid and pore pressure. In the 1940s, Gassmann proposed the elastic modulus formula of the fluid-filled in the pore rock, which laid the foundation for the study between the elastic theory and the petrophysical properties of modern sedimentary rocks [7, 8].

The rock acoustic wave testing technology is based on the correlation between the propagation characteristics of sound waves in the rock mass and the physical and mechanical parameters of the rock mass (sonic wave velocity, attenuation coefficient, waveform, frequency, spectrum, amplitude, etc.). The physical and mechanical properties of rock are evaluated by measuring the propagation parameters of sound waves in rock mass.

The sonic test is divided into longitudinal and transverse wave tests. The sound waves generated by the sound source radiate to the rock mass, causing the rock mass to vibrate, receive by the receiving transducer and convert its mechanical vibration into a weak electrical signal. After processing, the propagation speed of the longitudinal wave and the transverse wave in the medium can be calculated. The frequency range used for sonic testing is typically kHz to MHz, even up to GHz, and low frequency tests currently below 2 kHz also has been of attention.

3. Principle and application of rock acoustic wave testing

Acoustic wave testing is one of the effective ways to study the physical and mechanical properties, structural integrity and homogeneity of rock. Acoustic waves have the advantages of good directionality, high energy, low energy propagation loss, large propagation distance and strong penetrating power, which are a good information carrier and therefore have strong advantages in the field of rock testing. Formed in the late 1960s, the rock acoustic wave testing technology has been widely used in the field of engineering [4, 5, 9, 10].

This paper summarizes the domestic and foreign literatures and explains the principle and application of rock acoustic wave testing technology from three main application directions: physical parameter measurement, mechanical property research and anisotropy test.

3.1. Physical parameter determination

By testing the propagation velocity of longitudinal and transverse waves in the rock, parameters such as dynamic Young's modulus and Poisson's ratio can be determined. By using the propagation velocity and attenuation characteristics of acoustic waves, the composition and internal porosity of the rock can be studied. So, we can judge the integrity of rock mass or rock and attain rock classification and grading [11-13].

The essential factor affecting the elastic parameters of rock is the coupling of solid medium and its structure and fluid. Different elastic parameters have different responses to fluid and deformation. The main causes of the difference between the longitudinal and transverse wave velocity ratios or the longitudinal wave velocity of the rock mass are lithology, fissures, bedding planes, etc. [14, 15]. In general, the fast wave velocity indicates that the rock mass is dense, hard, complete, and light in weathering; on the contrary, it indicates that the rock mass is loose, weak, broken, structurally developed, and weathered seriously [2-4]. Therefore, based on the correlation between rock acoustic wave velocity and dynamic elastic mechanics parameters, combined with dynamic and static relationships, the static mechanical parameters of rock can be estimated, which is used for engineering applications such as engineering rock mass stability calculation, underground geotechnical engineering design and construction, etc. For example, Khazanehdari etc. conducted sonic in-situ testing of sandstone reservoirs, confirming the reliability of sound wave monitoring gas reservoir
capacity [16]. Cerrillo etc. used acoustic wave technology to estimate the physical and mechanical properties of granite, which provided a new basis for better understanding of geological materials such as granite and a clearer understanding of its environmental sensitivity, durability and safe useability [17].

3.2. Mechanical properties research
After more than 50 years of development, researches about the relationship between acoustic wave velocity and rock mechanics characteristics is still in the exploration stage. P-wave velocity, Young's modulus and strength are different macroscopic performances of rock specimens. They usually have positive correlation, but there is no certain mechanical relationship, and there are a lot of special cases. At present, there is also a lack of circumstantial evidence of acoustic parameters related to rock mechanics in addition to sound velocity. Therefore, acoustic testing is difficult to solve the complex problem between acoustic and rock mechanics [13,18,19].

At present, the acoustic wave method has been widely used in the testing of engineering rock mass damage range. Using the speed of sound to determine the integrity factor of rock mass, as an important indicator of rock mass quality classification, has been included in the national standard of engineering rock mass classification in China [9]. Through the study of the variation law of acoustic parameters during rock compression, the acoustic wave characterization of rock deformation and failure is realized. This is of great significance for the sound wave detection of underground engineering and the fine structure of seismic exploration, monitoring the rock deformation around the bridge and tunnel, predicting the stability of geotechnical engineering and ensuring the safe mining of underground resources, which is of great significance for the sound wave detection of underground engineering and the fine structure of seismic exploration, monitoring the rock deformation around the bridge and tunnel, predicting the stability of geotechnical engineering and ensuring the safe mining of underground resources.

3.3. Anisotropy test
In the rock medium, there are anisotropic features due to the existence of certain directional joints and fissures. The sound waves propagate in the rock medium and thus show directionality, and the difference in different directions is extremely obvious. Thill (1969) first studied the variation of acoustic longitudinal wave velocity with crack direction in rock and proposed a method to determine rock wave velocity anisotropy [20].

Sayer and Oda formed two main directions in the theoretical study of rock acoustic wave anisotropy. Sayer made semi-quantitative analysis to solve the fracture orientation problem, which proposed the pole figure inversion theory, established the relationship between the elastic constant and the crack distribution function, and found that the acoustic pole figure has a good correspondence with the crack pole figure through numerical calculation, and further the mechanical mechanism and damage process of fractured rock mass are studied [21-25].

Japanese scholar Oda proposed that the rock mass should be treated as anisotropy. From the point of view of the joint crack of the rock mass, the fracture tensor must first be used to represent the geometry fracture (fracture density, size, orientation) in the rock mass. The tensor that characterizes the change of wave velocity with the direction of the anisotropic body is creatively introduced. Based on the experiment, the empirical relationship between the crack tensor and the crack tensor is established, and the macroscopic mechanical parameters of the fractured rock mass are calculated by using the fracture tensor [26-28]. This method is widely used by the academic community.

The study of the anisotropic development of rock is used to clarify the relationship between acoustic directionality and rock anisotropy, which is of great significance for the use of acoustic testing data to guide actual resource exploration and geotechnical engineering.
4. Progress in theoretical experimental research

4.1. Physical property correlation

The existing petrophysical theory is based on the Gassmann equation and Biot's two-phase medium wave theory. Wyllie's time-averaged formula, White's gas inclusion model, Dvorkin's BISQ model and Connell's jet flow model can all describe the effect of pores on rock elastic characteristics, and greatly enrich and perfect the propagation theory of the elastic wave of saturated rock media theoretically [29-34].

For anisotropic fractured rock masses, the relationship between wave velocity and mechanical parameters becomes complex. Walsh, Connell, Hudson, and Kemeny established the relationship between the fracture density and the effective elastic parameters of the medium [34-38]; Budiansky and Zimmeran systematically established the theory relationship of crack density, equivalent elastic parameters and wave velocity [39, 40].

In order to study the relationship between wave velocity and density, experts and scholars have done a lot of exploration and improvement. Domestic scholars use the speed-density basic model proposed by Cardner and Castagna to derive many empirical relationships suitable for different lithologies in different regions, such as Chen Xu, Xiong Jian, Li Weixin, etc. through analyzing the experimental test data of different cores in different regions, studied the relationship between velocity and density, and the empirical relationship was obtained [5, 14, 29, 41].

In the physical mechanics of coal-based rocks, Meng Zhaoping and Zhu Guowei studied the relationship between the physical and mechanical parameters of coal-based rocks and the acoustic velocity [42-44]. Guo Deyong, Zhao Qun and Dong Shouhua etc. studied the anisotropic characteristics of coal longitudinal wave velocity and the anisotropic characteristics of coal rock attenuation coefficient and shear wave velocity [45, 46].

Some scholars have studied from their respective perspectives, such as the influence of water content on different rock acoustic parameters [47-48], the relationship between temperature and physical properties such as different lithology wave velocity and Young's modulus [49-52], which have become a hot spot for geophysicists today.

4.2. Physical property correlation

The variation of wave velocity, energy and spectral characteristics of acoustic waves propagating in rock media is an important basis for studying the mechanical properties of media, structural integrity and homogeneity of media. It is a hotspot of many scholars in recent years, and it is also a difficult point in theoretical research. But now, still no theoretically perfect mechanical model has been obtained [4]. The research of foreign scholars has shown that the acoustic wave and the mechanics have a nonlinear complex relationship due to rock fissures.

Domestic research on wave velocity-stress correlation began in the 1970s. Peng Suping, Lin Yingsong, Wang Hongtu, Shan Yuming, You Mingqing, Liu Xiangjun etc. studied the static parameters, wave velocity, dynamics of rock media characteristics and interrelationships between parameters [13,18,53-56]; Zhao Mingjie., Cai Meifen., Liu Weigu etc. researched about the variation of rock longitudinal wave velocity and rock fissure and its mechanical properties, the evolution of fissures, the classification of rock mass strength and rock body damage (integrity) is discussed [9,10,19, 57, 58].

For the elastic wave velocity and attenuation characteristics of rock mass under stress, a lot of work has been done at home and abroad, mainly through the aforementioned anisotropy angle; another researcher has studied the stress-crack by loading-unloading process, calibration experiment and other methods. The correlation between the damage process and the sound wave, and the ideal functional relationship is obtained, and will not be described here.

Most of the previous research results are based on the ultrasonic frequency band. Because the rock has the dispersion characteristics, there is a certain difference between the measurement results in the kHz to MHz frequency band and the data in the 5-100 Hz frequency band. In the direction of low-
frequency petrophysical experiments, Tutuncu etc. first tested the longitudinal and shear wave velocities of a salt-saturated sandstone from 10 Hz to 1 MHz. The results show that the velocity has an increasing trend. On this basis, Batzle etc., Dvorkin, Müller, Wang, Wei, He etc. have successively carried out research using low-frequency stress-strain methods [59-66].

5. Conclusion
Rock acoustic wave testing technology has become a research hotspot in academic and engineering fields. However, there are still some problems in China's rock acoustic wave testing technology, which can be summarized into the following three aspects:

- China's basic aspects of rock acoustic wave testing equipment and technical conditions are still poor, which hinders further understanding of rock acoustic characteristics and cutting-edge research work.
- For the complexity of rock media, it is still a major issue to establish a rock physics model that reflects the state of the original rock with wide applicability.
- The researches of rock acoustic wave testing technology are developing in the direction of multi-disciplinary and multi-method comprehensive application. The problem that how to systematically develop rock acoustic wave testing technology from qualitative to quantitative research makes this technology a mature engineering application science, which are important issues researchers face with.

Acoustic rock physics testing technology attracts researchers to explore with many advantages and good prospects, and has made great progress in theoretical research, experimental measurement and field application. However, from the perspective of academic research, it is inevitable that there are divergences and different opinions in various aspects. In this paper, there are inevitable shortcomings in the literature search and summary, which is only for the reference of research experts and scholars. Please testify if there is any inappropriate.

Acknowledgments
The authors acknowledge the Open fund of China State Key Laboratory of Water Resource Protection and Utilization in Coal Mine (Grant:SHJT-16-30.1) and State Key Research Development Program of China (Grant: 2016YFC0501102).

References
[1] Zhou, Z.G., Zhu, H.H., Chen, W. (2006) Experimental study on acoustic wave propagation character of water saturated rock samples. Chin. J. ock Mecha. Eng., 25:911–917.
[2] Wang, R.J. (1997) Analysis of acoustic rock classification and rock dynamic elasticity parameters. Geological Publishing House, Beijing.
[3] Chen Y., Huang T.F., Liu E.R.. (2009) Petrophysics. Press of University of Science Technology. China, Hefei.
[4] Zhao M.J., Xu R. (2000) The Present situation and Prospect of the acoustic properties research in rock. J. chongqing jiaotong instit., 19:79–85.
[5] Chen X., Yu J., Li H., Cai Y.Y., Zhang Y.Z., Mu K. (2013) Experimental study of propagation characteristics of acoustic wave in rocks with different lithologies and water contents. Rock Soil Mecha., 34:2527–2533.
[6] Ma Z.G., Zhou W., Sun C.L. (2006) The design and implementation of the software package for rock physics analysis. Geophys. Geochem. Explorat., 30:260–265.
[7] Toksäz, M.N. (1976) Velocities of seismic waves in porous rocks. Geophysics,41:621.
[8] Gassmann, F. (1951) Elastic waves through a packing of spheres. Geophysics,16:673–685.
[9] Zhao M.J. (1999) A study on ultrasonic properties of cracked rockmass under loading and unloading. Chin. J. Rock Mecha. Eng., 18:238–238.
[10] Zhao M.J., Xu R. (2000) The rock damage and strength study based on ultrasonic velocity. Chin. J. Geotech. Eng., 22:720–722.
[11] You M.Q., Su C.D., Shen J. (2001) Effect of heterogeneity on the dynamic parameters of rock. J. Liaoning Techn. University (Natu. Sci.), 20:492–494.
[12] You M.Q., Su C.D., Yang S.Q. (2002) Relation between static and dynamic parameters of rocks. J. Jiaozuo Instit. Tech. (Natu. Sci.), 21:413–419.
[13] You M.Q., Su C.D., Li X.S. (2008) Study on relation between mechanical properties and longitudinal wave velocities for damaged rock samples. Chin. J. Rock Mecha. Eng., 27:458–467.
[14] Xiong J., Liang L.X., Liu X.J., Ran W., Wu T. (2014) Experimental Study on Acoustic Penetration through the Longmaxi Formation Shale Rock in South Region of Sichuan Basin. Chin. J. Undergro. Space Eng., 10:1071–1077.
[15] Li H.M. (2014) The application of elastic parameters direct inversion to reservoir fluid identification. Geophys. Geochem. Explorat., 38:970–975.
[16] Cerrillo, C., Jiménez, A., Rufo, M., et al. (2014) New contributions to granite characterization by ultrasonic testing. Ultrasonics, 54:156.
[17] Khazanehdari J., Mccann C. (2005) Acoustic and petrophysical relationships in low-shale sandstone reservoir rocks. Geophys. Prospe., 53:447–461.
[18] Peng S.S., Xie H.P, He M.C., Zhang S.H. (2005) Experimental study on velocity characteristics of lithofacies transition rock mass. Chin. J. Rock Mecha. Eng., 24:2831–2837.
[19] Zhao M.J., Wu D.L. (2000) The ultrasonic identification of rock mass classification and rock mass strength prediction. Chin. J. Rock Mecha. Eng., 19:89–92.
[20] Thill R.E., Bur T.R., Steckley R.C. (1973) Velocity anisotropy in dry and saturated rock spheres and its relation to rock fabric. Int. J. Rock Mecha. Min. Sci. Geomech. Abst., 10:535–557.
[21] Sayers C.M. (2000) Ultrasonic velocities in anisotropic polycrystalline aggregates. J. Physics D Applied Physics, 15:2157–2167.
[22] Sayers C.M. (2002) Stress-dependent elastic anisotropy of sandstones. Geophys. Prospe., 50:85–95.
[23] Sayers C.M. (2005) Seismic anisotropy of shales. Geophys. Prospe., 53:667–676.
[24] Sayers C.M., Boer L.D.D. (2012) Characterizing production-induced anisotropy of fractured reservoirs having multiple fracture sets. Geophys. Prospe., 60:919–939.
[25] Sayers C.M. (2015) Fluid-dependent shear-wave splitting in fractured media. Geophys. Prospe., 50:393–401.
[26] Oda M. (1985) Permeability tensor for discontinuous rock masses. Geotechnique, 35:483–495.
[27] Oda M., Yamabe T., Kamemura K. (1986) A crack tensor and its relation to wave velocity anisotropy in jointed rock masses. Int. J. Rock Mecha. Min. Sci. Geomech. Abst., 23:387–397.
[28] Oda M. (1988) An experimental study of the elasticity of mylonite rock with random cracks. Int. J. Rock Mecha. Min. Sci. Geomech. Abst., 25:59–69.
[29] Ma Z.G., Deng D.J. (2003) Research in rock physical properties. Progress Explorat. Geophys., 26:387–401.
[30] Wyllie M.R.J. (1962) Studies of Elastic Wave Attenuation in Porous Media. Geophysics, 27:569–589.
[31] White J.E. (1975) Computed seismic speeds and attenuation in rocks with partial gas saturation. Geophysics, 40:224.
[32] Dvorkin J., Nur A. (1993) Dynamic poroelasticity: a unified model with the squirt and the Biot mechanisms. Geophysics, 58:524–533.
[33] Dvorkin J., Nolenhoeksema R.C., Nur A. (1994) The squirt–flow mechanism; macroscopic description. Geophysics, 59:428–438.
[34] O'Connell R.J., Budiansky B. (1977) Viscoelastic properties of fluid–saturated cracked solids. J. Geophys. Research, 82:5719–5735.

[35] Walsh J.B. (1965) The effect of cracks on the compressibility of rock. J. Geophys. Research, 70:381–389.

[36] Walsh J.B. (1981) Effect of pore pressure and confining pressure on fracture permeability. Int. J. Rock Mecha. Min. Sci. Geomech. Abstr., 18:429–435.

[37] Hudson J.A. (2010) Overall elastic properties of isotropic materials with arbitrary. Geophys. J. Int., 102:465–469.

[38] Kemeny J., Cook N.G.W. (1986) Effective moduli, non–linear deformation and strength of a cracked elastic solid. Int. J. Rock Mecha. Min. Sci. Geomech. Abst., 23:107–118.

[39] Budiansky B., O'Connell R.J. (1976) Elastic moduli of a cracked solid ☆. Int. J. Solids Structures, 12:81–97.

[40] Zimmerman R.W. (1985) The effect of microcracks on the elastic moduli of brittle materials. J. Mater. Sci. Lett., 4:1457–1460.

[41] Li W.X., Shi G., Wang H., et al. (2007) The study on the relationships of elastic properties of rock physics. Progress in Geophys., 22:1380–1385.

[42] Meng Z.P., Zhang J.C., Joachim T. (2006) Relationship between physical and mechanical parameters and acoustic wave velocity of coal measures rocks. Chin. J. Geophys., 49:1505–1510.

[43] Guo D.Y., Han D.X., Feng Z.L. (1998) Experimental study on wave velocity characteristics of structural coal under confining pressure. Coal sci. tech., 26:21–23.

[44] Dong S.H. (2008) Test on elastic anisotropic coefficients of gas coal. Chin. j. geophys., 51:341–346.

[45] Zhu H.H., Zhou Z.G., Deng T., et al. (2005) Acoustic parameters of low-porosity rock under dry and saturated conditions. Chin. J. Rock Mecha. Eng., 24:823–828.

[46] Wang D.X., Xing K.F., Li Y.M., et al. (2006) An experimental study of influence of water saturation on velocity and attenuation in sand-stone under stratum conditions. Chin. J. Geophys., 49:908–914.

[47] Du S.J., Ma M., Chen H.H., Qiu Y.P. (2003) Testing study on longitudinal wave characteristics of granite after high temperature. Chin. J. Rock Mecha. Eng., 28:560–568.
[55] Wang H.T., Li X.H., Yang C.H., Hu G.Z., Jia J.Q., Xue Z.X. (2005) The influence of cracks on the propagation properties of elastic waves in quasi-isotropic cracked rock masses. Rock Soil Mecha., 26:873–876.

[56] Shan Y.M., Liu W.G. (2000) Experimental study on dynamic and static mechanics parameters of rocks under formation conditions. J. chengdu university Tech., 27:249–254.

[57] Cai M.F. (2002) Rock mechanics and Eng.. Science Press, Beijing.

[58] Liu W.G., Shan Y.M., Fu R.H., Zhou J.J., Chang S.H., Su J.M.. (2003) A study of the relationship between the dilatancy of rocks and the characteristic parameters of ultrasonic wave. J. chengdu university tech., 30:87–91.

[59] Wei X., Wang S.X., Zhao J.G, Tang G.Y., Deng J.X. (2015) Laboratory study of velocity dispersion of the seismic wave in fluid-saturated sandstones. Chin. J. Geophys, 58:3380–3388.

[60] Tutuncu A.N., Gregory A.R., Sharma M.M., et al. (1998) Nonlinear viscoelastic behavior of sedimentary rocks, Part I: Effect of frequency and strain amplitude. Leading Edge, 63:184–194.

[61] Batzle, Han, Hofmann. (2006) Fluid mobility and frequency–dependent seismic velocity – Direct measurement. Geophysics J. Society Exploration Geophysicists, 71:N1.

[62] Dvorkin J. (2009) The Rock Physics Handbook, Second Edition. Cambridge University Press, Cambridge.

[63] Müller T.M., Gurevich B., Lebedev M. (2010)Seismic wave attenuation and dispersion resulting from wave–induced flow in porous rocks — A review. Geophysics, 75:75A147–75A164.

[64] Wang S.X., Zhao J.G., Li Z., et al. (2009) Differential Acoustic Resonance Spectroscopy for the acoustic measurement of small and irregular samples in the low frequency range. J. Geophys. Research Solid Earth, 117:B6.

[65] Wei X., Wang S.X., Zhao J.G., et al. (2015) Laboratory study of velocity dispersion of the seismic wave in fluid–saturated sandstones. Chin. J. Geophysics, 58:3380–3388.

[66] He Y.L., Peng S.P., Du W.F, et al. (2017) Laboratory Study of Acoustic Velocity in Different Types of Rocks at Seismic Frequency Band. Sains Malaysiana, 46:2187–2193.